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THE MSC CSM ELECTRICAL POWER SUBSYSTEM PROGRAM

(SEENA)

By Roy E. Stokes,
Guidance and Performance Branch

MISSION PLANNING AND ANALYSIS DIVISION

MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

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PROJECT APOLLO

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THE MSC CSM ELECTRICAL POWER SUBSYSTEM PROGRAM

By Roy E. Stokes

SUMMARY AND INTRODUCTION

This note presents specifications for programing of the MSC CSM electrical power subsystem program (EPS) which will solve the CSM-EPS distribution circuit. This program should be used for all EPS consumables analyses and contingency studies. A description and general flow charts of each of the subroutines are given. This program will replace the present CSM-EPS program which is now out of date because of changes in the EPS equivalent circuit. The MSC CSM-EPS program should be faster to minimize computer time and more flexible to allow for changes in the EPS circuit. In addition the program should be designed so it can be used to solve EPS circuit parameters for the Apollo Applications Program (AAP) with a minimum of program changes.

This report presents preliminary EPS circuit data and a preliminary schematic drawing of the EPS circuit. This data is being used for the initial design of the MSC CSM-EPS program; updates to the data will be published as they become available.

PROGRAM DESIGN

The MSC CSM-EPS program is to be made as flexible as possible so that future changes in the CSM-EPS circuit will not cause major program modifications. The program will be designed for use on the Univac 1108 computer and will be capable of solving the EPS circuit parameters for AAP with a minimum of program changes. Minimum computer time needed to run the MSC CSM-EPS program should be one of the main objectives of the computer programer.

Program flexibility is to be obtained by generalizing as many subroutines as possible. The only subroutines that need to be changed for different CSM circuits are those which input the circuit equations and constraints on the switches in the EPS circuit.

Appendix A presents preliminary data which is to be used for the initial design of the MSC CSM-EPS program. A preliminary schematic of the EPS circuit is also given. The switching logic and an example of how it is to be used in determining the first guess voltage are given in appendix B. The equations for the EPS circuit matrix are presented in appendix C.

The output of the EPS program will be set up with clearly labeled tables. There will be two output sections; one for consumables studies and the other for contingency studies. The contingency studies output may be omitted for a time event, but the consumables study output may never be omitted.

The MSC CSM-EPS program will eliminate most of the shortcomings of the present CSM-EPS program. The program will allow for oxygen and hydrogen used in fuel-cell purges. The battery charger and the fuel cell reverse-current and overload-current relays will be simulated. The diode resistances of the new CSM circuit will be included in the circuit equations if these resistances are found to be significant. An attempt is being made to obtain better voltage current data for all the sources used. Also, better bus tie equivalent resistance data is being sought. The new CSM-EPS program will simulate the inverters more accurately than the present CSM-EPS program.

The MSC CSM-EPS program must have the capability of computing EPS circuit parameters while the source (fuel cells and batteries) characteristics vary with time. Changes in the fuel cell characteristics occur as the load current demanded from the fuel cell changes from time event to time event. The change in fuel cell load current causes the fuel cell temperature to vary, which causes the fuel cell output characteristics to vary. The variation of the fuel cell output characteristics continues until the fuel cell temperature becomes stable. The thermal response of the fuel cells causes the output characteristics to be time dependent. The steady state data is to be used only if the data needed for the fuel cell temperature response model is not found by the time the program is needed by the Consumables Analysis Section (CAS) of Mission Planning and Analysis Division (MPAD). The entry and postlanding battery characteristics vary as the discharge characteristics of the batteries change with time. The program must simulate the entry and postlanding batteries discharge characteristics.

The present CSM-EPS program timeline writer is a very flexible subprogram, and the timeline writer subprogram for the MSC CSM-EPS program must be at least as flexible. The new timeline writer should be designed to accept 50 subsystems, 60 components per subsystem, any component bus assignment, and 6 component modes. The timeline writer must also have the capability to turn on and off the alternating current only or the direct current only of components using both ac and dc power. When the computer programer develops the timeline writer subprogram, he should bear in mind two main objectives; first, ease in program update and second, minimum computer operation time.

The present CSM-EPS program could plot many of the output parameters on the Calcomp plotter. The MSC CSM-EPS program should be capable of plotting all the output parameters versus time and also various output parameters versus other output parameters stored on an EPS output tape. The Univac DD80 will be used to make the plots for the MSC CSM-EPS program.

The program should solve circuit parameters in both the SM and CM after CSM separation. The program flexibility of solving two separate circuits (which may at times be connected making only one circuit) will be needed in EPS circuit modeling for AAP.

The following is an example of possible program input data:

(1) Subsystem.

(2) Component.

(3) Mode.

(4) ac or dc component.

(5) Bus connection of component.

(6) Power factor if component requires ac power.

(7) Transient power and time for the transient power of the component to deplete.

(8) Steady state power of component.

(9) Overload limits on the buses, subsystems, and fuel cells.

(10) Hydrogen and oxygen cryogenic loading and tank fail flag.

(11) Any data necessary to increase programing efficiency.

MSC CSM-EPS cold plate data for the present CSM environmental control system (ECS) program will be calculated and stored in the same manner as the present CSM-EPS program.

Program checks and comment cards should be used throughout the MSC CSM-EPS program. An additional requirement is for a program restart capability. The techniques to be used for this procedure must be coordinated with CAS of MPAD before incorporation into the program.

MASTER CONTROL SUBROUTINE (MCS)

The MCS (flow chart 1) must read in and process all loadsheet parameters, component inventory data, and timeline data. The component inventory data is read into the correct computer storage arrays according to the assigned volt code. The timeline data is to be processed time event by time event. Program flags are then set; the flags are to be in a subroutine of the MCS. Components are processed in the ac components processing subroutine (ACCPS) and the dc components processing subroutine (DCCPS) which are called for by the MCS. A power profile may be called for and generated on the plot tape in the MCS.

Flag Subroutine (FS) - Called by MCS

The FS is used to eliminate program errors caused by having false information stored in the computer memory. The FS logic is presented in flow chart 2. The following flags are available from the FS.

(1) Set all ac and dc bus-overload flags to indicate no overload.

(2) Set all ac and dc subsystems overload flags to indicate no overload.

(3) Set battery charger in off status. (This status is to be checked in the charger subroutine.)

(4) Set all battery discharge energies to zero.

(5) Set fuel cell energy at zero.

(6) Set total system energy consumption at zero.

(7) Set all switches to zero or off.

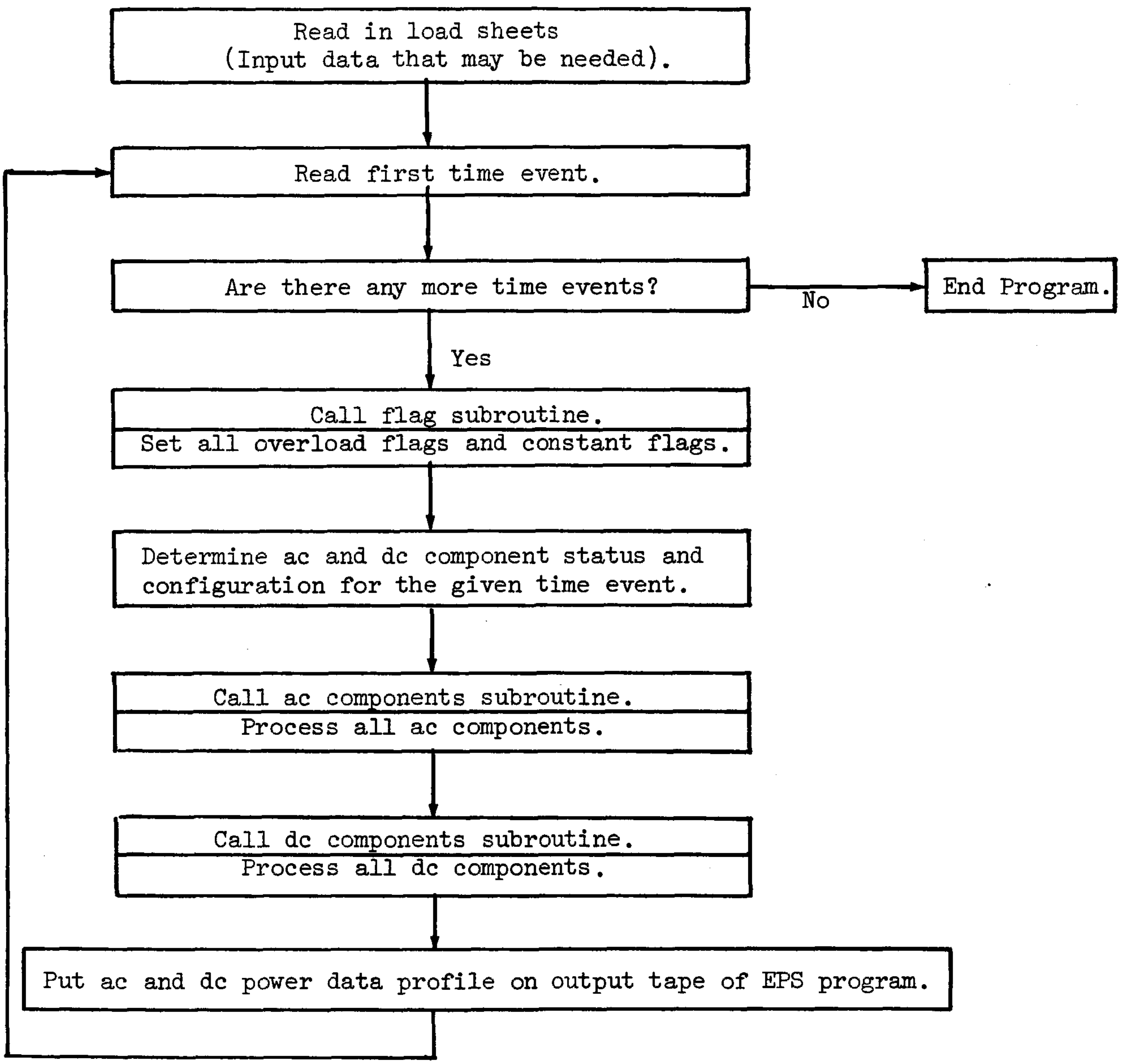
(8) Set charging energy at zero (to be checked on in charger routine).

(9) Set cumulative H_2 and O_2 used to zero.

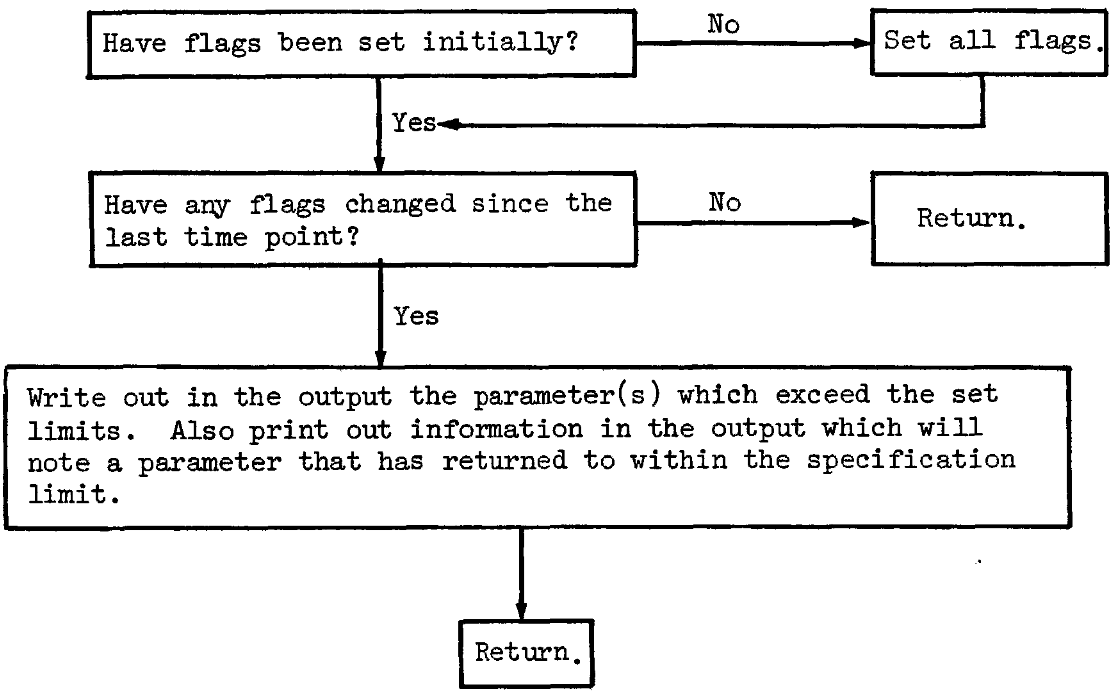
(10) Set H_2 and O_2 tank fail to zero which is nonfail.

(11) Set H_2 and O_2 consumption rate to zero.

(12) Set discharge power of batteries to zero.



Flow chart 1.- Master control subroutine.



Flow chart 2.- Flag subroutine.

(13) Set total fuel cell power level to zero.

(14) Set battery charger amperage to zero.

(15) Set battery discharge amp hours to zero.

(16) Set battery currents to zero.

(17) Set fuel cell currents to zero.

(18) Set any overload or constant flags that are needed to facilitate programing needs.

Alternating Current Components Processing Subroutine (ACCPS) -

Called by MCS

The purpose of the ACCPS is to perform a load analysis at each time event in the mission profile. The loads on the ac buses and the dc power required by the inverters are to be determined by this subroutine. The subroutine will test the overload flags on the inverters and each of the ac subsystems. If an overload does occur, a printout of the flag violation will be demanded in this subroutine. The overload printouts will then be inhibited until the overload no longer exists. A second printout acknowledging the change in overload status will be made.

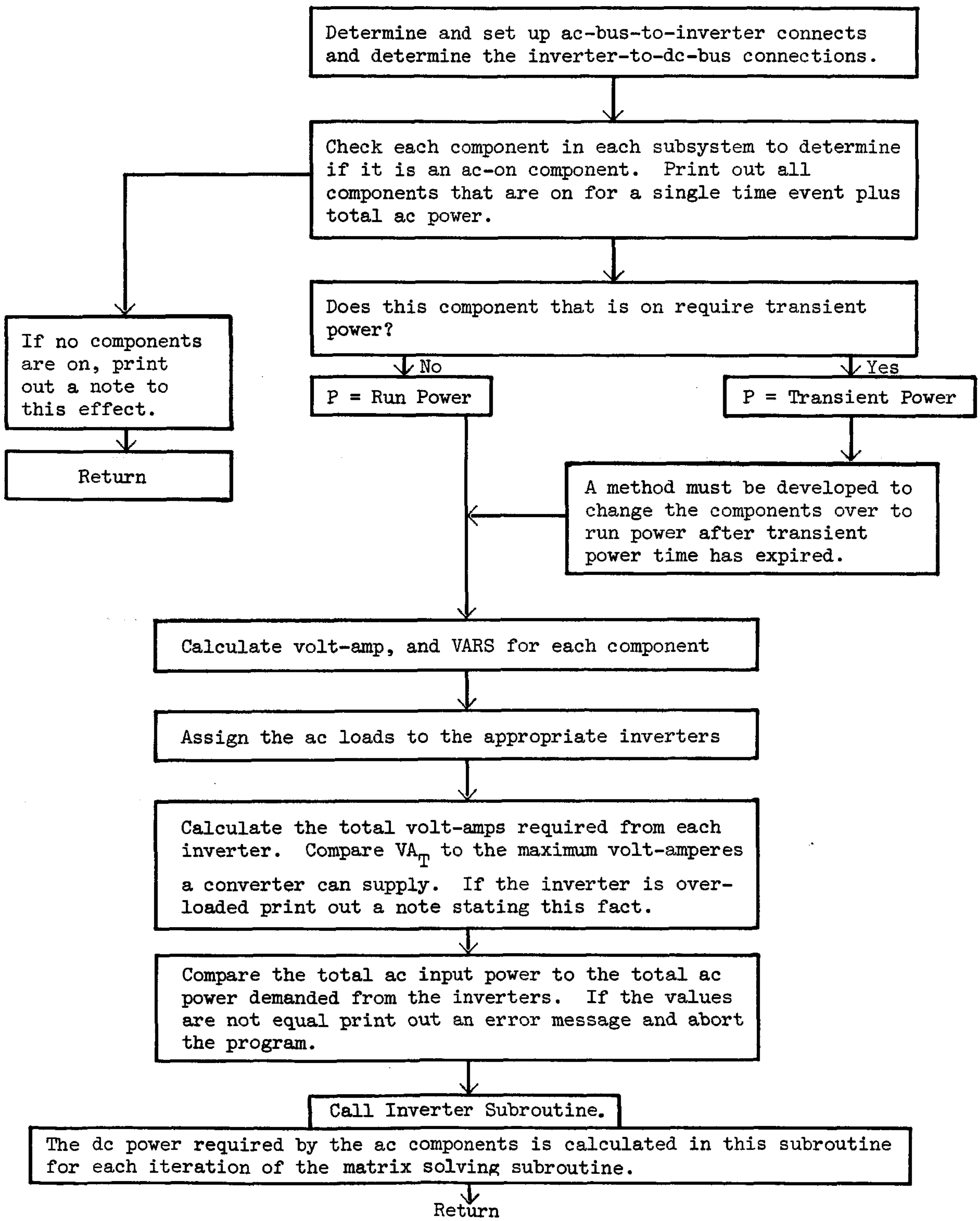
The subroutine will handle ac loads with various power factors and transient power demands. A program method must be developed which uses the transient power of a component for the circuit calculations until the time required by the transient power has been exceeded. The program calculations then are to be made using the steady state run power of the component.

The general logic for the ACCPS is given in flow chart 3. The method given in the following discussion is to be used to determine the dc power required by the ac inverters and the overload of any inverter or subsystem. For each component, the volt-amp (VA) and the reactive power (VARS) are to be calculated using equations (1) and (2).

$$VA = \frac{watts}{Pf} \tag{1}$$

$$VARS = (VA^2 - watts^2)^{\frac{1}{2}} \tag{2}$$

where Pf is the power factor.



Flow chart 3.- ac components process subroutine.

An inverter overload can be made by using the results of equations (1) and (2) in the following equation.

$$VA_T = \left[(\Sigma \text{ watts})^2 + (\Sigma \text{ VARS})^2\right]^{\frac{1}{2}} \qquad (3)$$

The total volt-amp loading, VA_T, for each inverter must not exceed 1250 volt-amp.

The dc equivalent power required by the components is to be found by using the inverter subroutine. Subsystem overload can be determined by comparing the maximum power allotted for the subsystem to the power required by the components.

The program should have the ability to produce an ac power profile from the data processed for each time event.

There are three inverters to contend with. The three inverters should have flexible ac and dc bus interconnections. For example, it should be possible for all three inverters to be connected to any of two dc or two ac buses, but two ac inverter outputs should never be paralleled. The possibility of turning the inverters on through an input card should be investigated.

Inverter subroutine (IS) - called by ACCPS and DS.- The IS will calculate the equivalent dc resistance of the ac power load on the inverter. The equivalent dc resistance will be a function of the bus voltage to which the inverter is connected.

The equivalent dc resistance is obtained by converting the ac power required into an equivalent dc power and then dividing the equivalent dc power into the voltage value squared of the bus to which the inverter is connected. The dc power required is found by dividing the ac power required by an efficiency factor. The efficiency factor varies as the load varies and also as the dc bus voltage to the inverter input varies. Therefore, a set of tables listing inverter efficiency versus inverter load for various dc input voltages must be used.

The initial dc equivalent resistance will be calculated using the final inverter input bus voltage from the previous time event. The first time event will use a nominal 28 volts as the first guess in the dc equivalent resistance calculation. A new inverter input dc bus voltage will be obtained for each iteration in the DCCPS. The new inverter input dc bus voltage will be used to obtain a new inverter efficiency which gives a new dc equivalent power. The new inverter input dc bus voltage and the new dc equivalent power will be used to obtain a new dc equivalent resistance for the inverter.

The preceding process will iterate in the DCCPS until the EPS circuit solution meets the accuracy specification demanded. Calculation of dc equivalent resistance in this manner greatly decreases the error introduced in the program due to the ac loads approaching the maximum and minimum watts output and due to the variations in the dc bus voltages to which the inverters are connected. Table I of appendix A contains the inverter volt-ampere loads as a function of efficiency.

Direct Current Component Processing Subroutine (DCCPS) -

Called by MCS

The DCCPS will determine which dc components are on and off and the status of the on components. Transient powers are to be contended with in this subroutine as they were in the ACCPS. The DCCPS controls the remaining solution of the CSM-EPS circuit. Flow chart 4 presents the DCCPS logic.

The DCCPS controls the entire solution of the EPS circuit matrix until an acceptable solution is rendered.

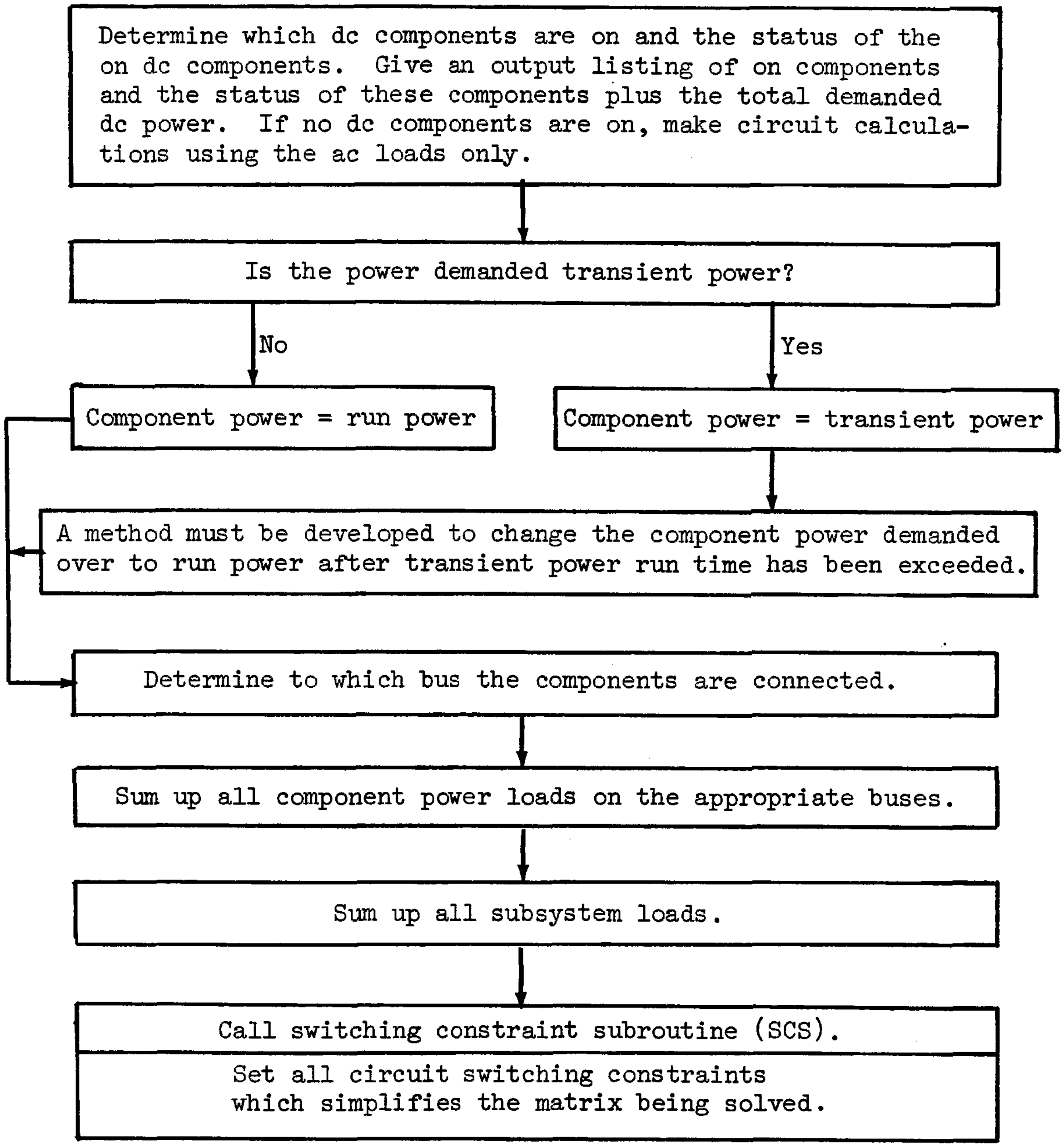
The DCCPS calls the switching constraints subroutine which is used to simplify the matrix being solved by the program. The switching constraints logic is given in table I of appendix B.

Equations subroutine (ES).- The ES calculates and lists the equivalent resistances of the circuit loads and the circuit equation coefficients which compose the matrix to be solved. Figure A-1 is a schematic of the EPS circuit; table A-II lists values of all circuit resistances. An initial diode voltage drop of 0.600 volts is to be assumed for the first calculation in a time event. The CSM-EPS equivalent load resistances (R_{eq}) are calculated by using the following equation.

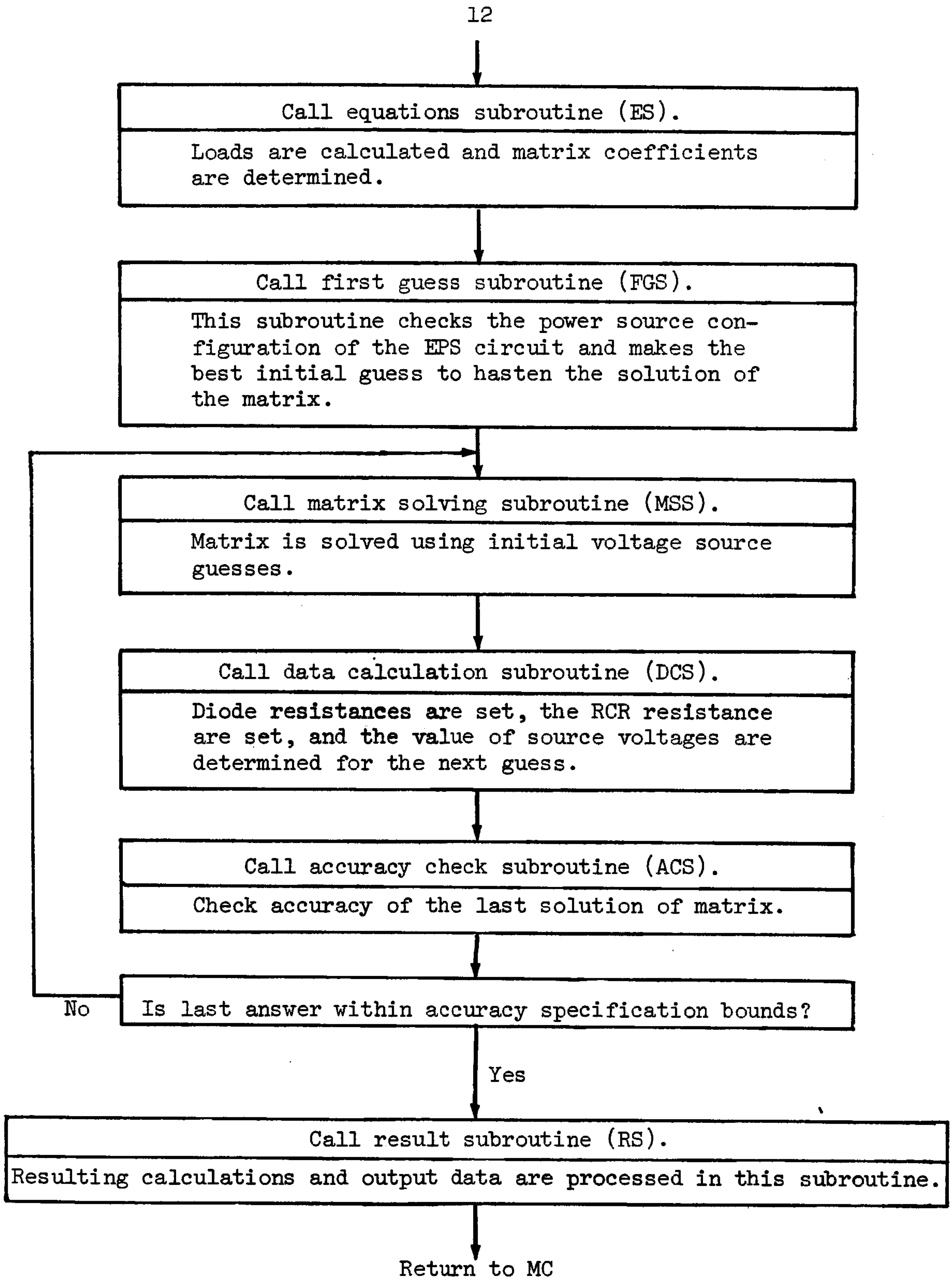
$$R_{eq} = \frac{(28)^2}{\text{power demanded by the particular load}} \tag{4}$$

The equations to be used for the initial design of this program can be found in appendix C.

First guess subroutine (FGS) - called by DCCPS.- Next, the DCCPS calls the FGS which is used to make a first logical guess of the source voltages which will enable the matrix solving subroutine (MSS) to more quickly solve the EPS circuit matrix.



Flow chart 4.- dc component process subroutine.



Flow chart 4.- dc component process subroutine - Concluded.

The FGS should make an initial source voltage guess which will be very close to the final or real source voltage. This will enable the program to converge on the matrix solution with a minimum of iterations, thus saving computer time.

The approach that will be used by this program will be one which matches an estimated source power load to the source voltage current tables (table A-III, A-IV and A-V). In order to use this method the demanded power loads of each bus must be determined and then an approximate load sharing scheme must be used to determine how much of the load is applied to each of the eight sources. The calculation of the demanded power on each bus can be determined in the component processing section of the DCCPS. Switching logic and program experimental results can be used to determine the estimated portion of the total load demanded that should be assigned to each source. An example of the switching logic to be used in determining the first voltage guess can be found in table B-II.

An alternate method may be used to obtain the estimated source power load for the sources in the CSM-EPS. This alternate method consists of substituting a unit voltage source for each one of the CSM-EPS sources that may be on during a given time event. The matrix will then be solved using the unit voltage sources. A resulting current can then be calculated for each unit voltage source. There is now enough information to determine the approximate equivalent resistance that each CSM-EPS will have as a load:

$$R = \frac{\text{unit source voltage}}{\text{unit source current}}. \tag{5}$$

All of the FGS switching logic could be eliminated if the estimated source load equivalent resistance was obtained in this manner. The first guess subroutine would still have to converge on a first guess voltage answer as is done in block 5 of the FGS flow chart.

Matrix solving subroutine (MSS) - called by DCCPS.- MSS is now called for. The MSS should be capable of solving as large a matrix as possible (at least 31 × 31) with accuracy to five digits.

The method used to solve the actual CSM-EPS circuit equations is one which iterates on source voltage guesses until it converges on an acceptable answer. First, the source current which is the result of the initial source voltage guess is located in the appropriate source voltage current characteristic table (tables A-III, A-IV and A-V). The voltage in the characteristic table which corresponds to the calculated current (resulting source current of the first guess) is then used as the next source voltage guess in the matrix being solved.

Determine the total load in watts applied to each group of sources (entry and postlanding batteries, pyro batteries, and fuel cells).

Find the load for each source:

$$\text{Load for each source} = \frac{\text{total load for particular source group}}{\text{number of sources on in the source group}}$$

Find the correct voltage current combination from the source characteristic table that equals the power demanded by the loads.

Power demanded = voltage × current

Find the equivalent resistance of the loads applied to the particular source. $R_{eq} = \dfrac{28^2}{\text{Power demanded by loads}}$

An iteration process is now used to converge on a proper first voltage guess. This is done by dividing the voltage obtained from the power demanded by the equivalent resistance, R_{eq}, and finding the resulting current value in the source voltage current table. The accuracy of this guess can be determined by comparing R_{eq} to the resistance calculated from the new voltage-current results. If this result is not accurate enough (to the second decimal place) the new voltage "V" is divided by R_{eq} and the subroutine iterates through the preceding process until the first-guess voltage meets the accuracy specification. The accuracy of the first-guess voltage is checked by comparing previous and present voltage results and monitoring changes in the fourth digit of the voltage guess results.

Return to DCCPS with first voltage guess.

Flow chart 5.- First guess subroutine.

The results of MSS are then put into the accuracy check subroutine (ACS). The ACS must make a test on the MSS results and then determine if the results are within the accuracy specification of five decimal places. If the results are not within specification, return to the MSS via data subroutine (DS) and iterate through the MSS and ACS until a desirable solution is found. Once a desirable solution is found, return to the DCCPS.

Accuracy check subroutine (ACS) - called by DCCPS.- The ACS will compare two values and determine the accuracy of the last answer obtained from the MSS. The two values to be compared by the ACS are the source voltage guess which will be used to solve for the next source voltage guess, and the source voltage guess for the previous iteration. The two values of source voltage will give a spectrum of the matrix conversion. The two values should be compared, to note when the fifth digit ceases to change. At this point the matrix can be said to be solved satisfactorily. Checks should be incorporated in this portion of the DCCPS to expedite the solution of the matrix being solved.

Data subroutine (DS) - called by DCCPS.- The DS for the next calculation simulates the reverse current relay (RCR) operation, the diode forward and reverse bias characteristics, and the new inverter equivalent load.

If the current through a diode is negative the equivalent resistance of the diode is on the order of 1 megohm. If the current through a diode is positive the equivalent resistance is calculated as a function of the current passing through the diode. Since the current through the diode is known, the voltage across the diode can be found from the diode volt-amp characteristic table. Once the diode voltage is determined it can be put into the matrix as a more accurate diode voltage drop guess. In order to make the initial calculation a diode voltage drop of 0.600 volts will be assumed. The diode resistance is determined by looking up the diode current in the diode steady state power loss versus diode current table and reading out a power which corresponds to the diode current. Then,

$$\text{diode resistance} = \frac{\text{diode steady-state power}}{(\text{diode current})^2}. \qquad (6)$$

The RCR equivalent resistance is on the order of 1 megohm after a reverse current of specific magnitude has passed through the RCR for a specified time limit given in table A-VI. If the current through the RCR is positive and does not exceed the limits set in table A-V the resistance will be assumed as 0.002 ohms[a]. If the positive current

[a]This is an approximation to be used until the RCR data is obtained.

exceeds the limits of table A-VII the equivalent RCR resistance is again 1 megohm. The DS will next call the IS. The IS will calculate the new inverter equivalent load resistance.

The DS also determines the next values to be used for the source voltages. This is done by calculating the current through the sources resulting from the last calculations made by the matrix solving subroutine. The calculated current values are then looked up in the source voltage current characteristic table, corresponding to the calculated current, is used for the next voltage guess.

RESULT SUBROUTINE (RS) - SUBROUTINE OF DCCPS

The RS calculates the necessary results. The RS will then output all results in two different categories. Category I will contain all information needed for a consumables study. Category II will list data necessary to make a contingency study. Category I will be called for at all times. Category II will be optional and called for only if signaled for. The following is a list of all the data needed in category I (consumables studies):

1. Power data:
   a. Instantaneous dc power.
   b. Instantaneous ac power and volt-amps.
   c. Total ac and dc power accumulated.
   d. Battery charge status[a].
2. Cryogenic data:
   a. EPS H_2 and O_2 instantaneous consumption rate.
   b. ECS O_2 instantaneous consumption rate.
   c. Remaining H_2 and O_2[b].
   d. Consumed H_2 and O_2[b].
   e. Cryogenic tank fail and non-fail.

---

[a]Battery charger subroutine data is used to obtain this value.

[b]The purge subroutine (PS) is used to aid the calculation of these values of H_2 and O_2.

3. Component data:

a. List all ac and dc components on. If no components, either ac or dc, are on, state this fact in the output.

b. List power demanded by the ac and dc components.

4. Power system overload data:

a. Overloads on fuel cells, and buses.

5. Fuel cell data:

a. Fuel cell voltages and consumption rate of H_2 and O_2.

b. Fuel cell temperature.

c. Fuel cell currents.

6. Battery data:

a. Battery voltages.

b. Battery current.

7. Give the time for the particular time event under study.

8. Bus voltages.

The following is a list of all the data needed in category II (contingency studies):

1. All consumables analysis data must be printed out plus the following information.

2. Voltage data:

a. Node voltages.

3. Current data:

a. Bus and node currents. (Bus and node currents are to be described specifically for each bus. Example:

(1) Current into the bus or node.

(2) Current to loads.

(3) Current to other nodes or buses.

4. Load sharing data: Printout the percentage of the total load that each source shares.

Battery Charger Subroutine - Called by RS

The battery charger and the battery that is being charged by the battery comprise a very complicated circuit. An approximation of the battery charger will be used for this program. This approximation deals only with the battery charger output. The input power of the battery charger is assumed to be constant.

Battery charger "on" mode switching constraints are as follows:

1. The battery charger can charge only one battery at a time.

2. All battery loads, connected to a battery which must be charged, must be disconnected from the battery before the battery charger can be used to charge the battery.

The following equation describes the general behavior of the battery charger:

$$AH_N = \frac{(T_1)\ (AH_0)}{AH_0 + 1} + (40 - AH_0) \tag{7}$$

where

AH_N = new charger status of the battery.

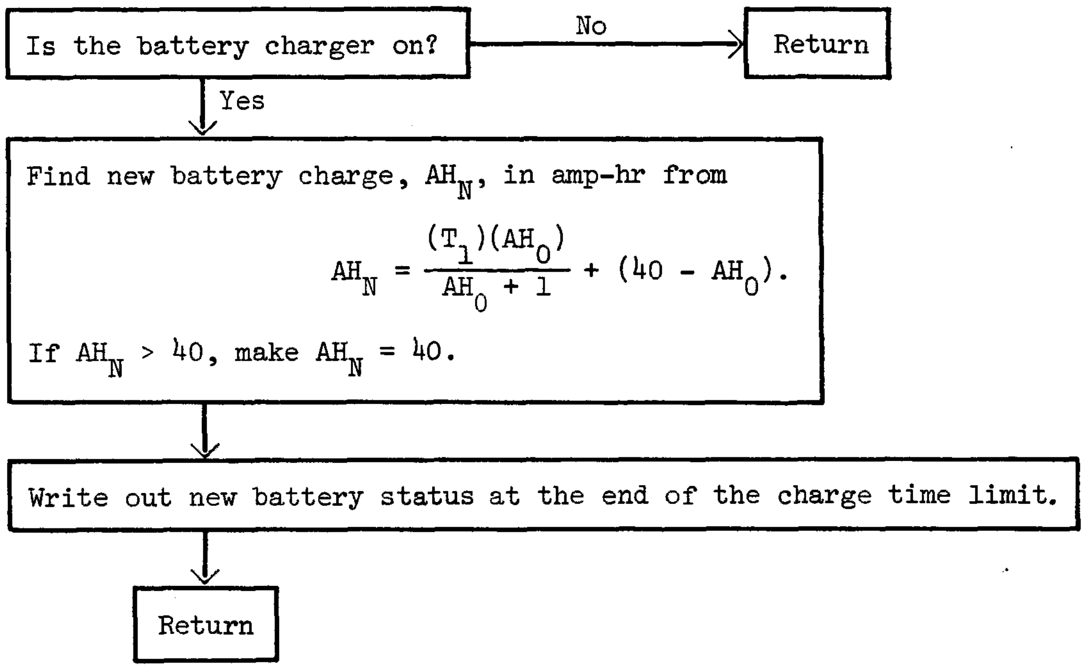
AH_0 = amount of ampere hours depleted from the battery.

T_1 = time the charger is left on.

This equation is to be used to calculate the charge status of a battery just after charge. AH_N maximum should never exceed 40 amp-hr. Using this equation, if AH_N >, make AH_N = 40 amp-hr.

Purge of Fuel Cells Subroutine (PFCS) - Subroutine of RS

First, the number of fuel cells operating must be determined by the PFCS, so that the correct H_2 and O_2 rates can be calculated. The purge



Flow chart 6.- Battery charger subroutine.

rate for H_2 is 0.67 lb/hr per fuel cell, and the purge rate for O_2 is 0.60 lb/hr per fuel cell. The allowed purge times are 80 seconds for H_2 and 120 seconds for O_2.

The general equations for the calculation of the pounds of H_2 and O_2 consumed by purges are:

$$H_2 = \left(\frac{80}{3600}\right) (0.67) \text{ (number of fuel cells)} \tag{8}$$

$$O_2 = \left(\frac{120}{3600}\right) (0.60) \text{ (number of fuel cells)} \tag{9}$$

The purge routine may be initiated by the identification of a purge component being turned on. New H_2 and O_2 data is to be given when the purge component is turned off.

APPENDIX A

EPS CIRCUIT DATA

TABLE A-I.- INVERTER LOADS

[Inverter efficiency, Pf = 1.0]

Load, V-amp	Efficiency, percent	dc input, v
100	63.20	25
200	67.50	25
250	69.00	25
300	70.25	25
350	71.60	25
400	72.50	25
450	73.30	25
500	74.00	25
550	74.80	25
600	75.50	25
650	76.00	25
700	76.50	25
750	77.00	25
800	77.25	25
850	77.50	25
900	77.73	25
950	77.77	25
1000	77.85	25
1050	77.90	25
1100	77.85	25
1150	77.77	25
1200	77.73	25
1250	77.50	25
1300	77.40	25
1350	77.25	25
1400	77.00	25
1900	72.10	25

TABLE A-I.- INVERTER LOADS - Continued

Load, V-amp	Efficiency, percent	dc input, v
100	59.50	28
200	65.00	28
250	66.60	28
300	68.25	28
350	69.60	28
400	70.65	28
450	71.60	28
500	72.50	28
550	73.35	28
600	74.25	28
650	74.90	28
700	75.50	28
750	76.00	28
800	76.40	28
850	76.70	28
900	76.80	28
950	77.00	28
1000	76.95	28
1050	76.80	28
1100	76.70	28
1150	76.60	28
1200	76.40	28
1250	76.25	28
1300	76.00	28
1350	75.75	28
1400	75.50	28
1900	71.90	28

TABLE A-I.- INVERTER LOADS - Concluded

Load, V-amp	Efficiency, percent	dc input, v
100	54.20	30
200	60.00	30
250	62.25	30
300	62.95	30
350	65.50	30
400	66.75	30
450	68.25	30
500	69.45	30
550	70.60	30
600	71.70	30
650	72.30	30
700	73.30	30
750	74.00	30
800	74.75	30
850	75.00	30
900	75.35	30
950	75.50	30
1000	75.60	30
1050	75.60	30
1100	75.50	30
1150	75.40	30
1200	75.20	30
1250	75.10	30
1300	74.95	30
1350	74.65	30
1400	74.45	30
1900	71.10	30

TABLE A-II.- CSM RESISTANCE VALUES

Resistor no.	Resistance, ohms
1	0.0100
2	0.0100
3	0.0100
4	0.0100
5	0.0100
6	0.0100
7	0.0100
8	0.0100
9	0.0100
10	0.0100
11	0.0100
12	0.00751
13	0.00607
14	0.00680
15	0.00451
16	0.0100
17	~~0.0050~~ .0915
18	~~0.0050~~ .0915
19	0.0100
20	0.0100
21	0.0100
22	0.0100
23	0.00451
24	0.0050
25	0.0100
26	~~0.0050~~ .0915
27	~~0.0050~~ .0915
28	0.0100
29	0.0100

TABLE A-II.- CSM RESISTANCE VALUES - Continued

Resistor no.	Resistance, ohms
30	0.00680
31	0.0100
32	0.0100
33	0.0100
34	0.0100
35	0.0050
36	0.0050
37	0.00451
38	0.00607
39	0.00751
40	0.0100
41	0.0100
42	0.0100
43	0.0100
44	0.0100
45	0.0100
46	0.0100
47	0.0100
48	0.0100
49	0.0100
50	0.0100
51	0.00465
52	0.0010
53	0.0010
54	0.0010
55	0.0093
56	0.0093

TABLE A-II.- CSM RESISTANCE VALUES - Concluded

Resistor no.	Resistance, ohms
57	0.0100
58	0.0024
59	0.0024
60	0.0024
61	0.0100
62	0.0024
63	0.0024
64	0.0024
65	0.0100
66	0.0055
67	0.0044
68	0.0055
69	0.0044
70	0.0055
71	0.0044

TABLE A-III.- VOLTAGE-CURRENT DATA FOR PYROTECHNIC

BATTERIES 1 AND 2

dc current, amp	dc voltage, v
1	30.45
6	30.4
15	29.2
25	28.
50	25.

TABLE A-IV.- VOLTAGE-CURRENT DATA FOR ENTRY AND POSTLANDING BATTERY

dc current, amp	dc voltage, v
0.0	32.0
0.45	31.8
1.0	31.6
1.6	31.4
2.3	31.2
3.0	31.0
4.9	30.8
6.8	30.6
8.7	30.4
10.6	30.2
12.5	30.0
14.9	29.8
17.3	29.6
19.7	29.4
22.1	29.0
24.5	29.0
28.8	28.8
33.1	28.6
37.4	28.4
41.7	28.2
46.0	28.0
50.8	27.8
55.6	27.6
60.4	27.4
65.2	27.2
70.0	27.0
74.6	26.8
79.2	26.6
83.6	26.4
88.0	26.2

TABLE A-V.- FUEL CELL STEADY STATE VOLTAGE-

CURRENT CHARACTERISTIC DATA

dc voltage, v	dc current, amp	Temperature, °F
36.00	0.	Not in operation range
31.75	7.50	Not in operation range
31.37	10.00	Not in operation range
30.25	15.00	Not in operation range
30.40	18.00	407.30
30.30	20.00	410.00
29.82	25.00	417.34
29.45	30.00	423.34
29.07	35.00	428.34
28.67	40.00	429.41
28.30	45.00	437.30
27.92	50.00	440.50
27.60	55.00	444.45
27.20	60.00	447.50
26.50	70.00	452.40
25.80	80.00	457.05
25.15	90.00	461.00

TABLE VI.- TABLE A-VI.- REVERSE-CURRENT DATA

Current, amp	Time, sec
4	No trip
20	2.10
30	1.22
50	1.11

TABLE A-VII.- OVERLOAD-CURRENT DATA

Current, amp	Time, sec
75	No trip
112	80.
150	38.
300	5.81
450	1.07
600	0.776
750	0.572
1000	0.470

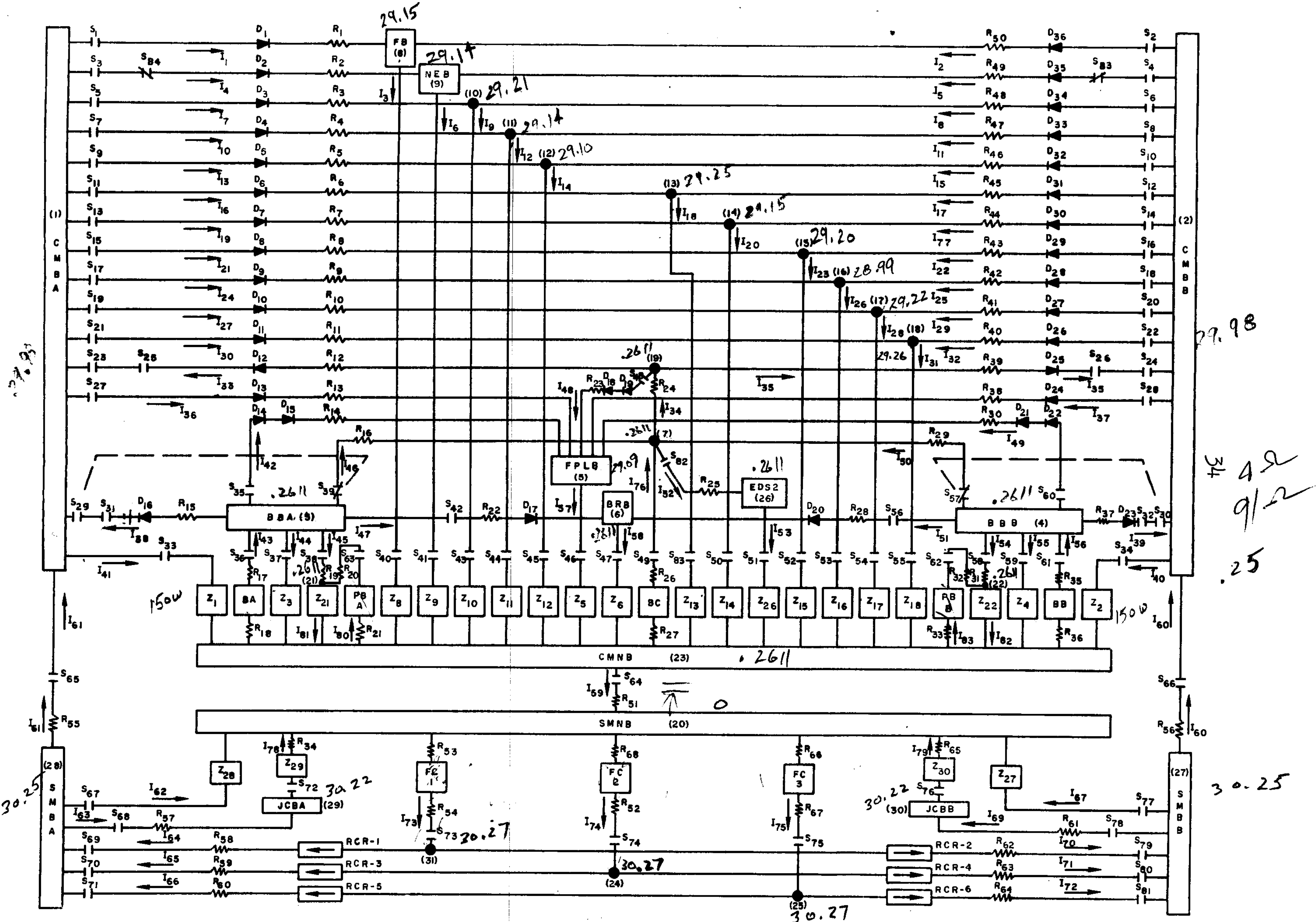


Figure A-1.- CSM equivalent circuit (Block II).

APPENDIX B

EPS SWITCHING LOGIC

APPENDIX B

EPS SWITCHING LOGIC

TABLE B-I.- SWITCHING LOGIC FOR ALL NODES

[If S = 0, switch is open; if S = 1, switch is closed.]

Node

(1) If S_{65} = either S_{29} or S_{31} = either S_{23} or S_{25} = 0, then $S_{33} = S_{27} = S_{21} = S_{19}$

$= S_{17} = S_{15} = S_{13} = S_{11} = S_{9} = S_{7} = S_{5} = S_{3} = S_{1} = 0$

(2) If S_{66} = either S_{32} or S_{30} = either S_{26} or S_{24} = 0, then $S_{34} = S_{28} = S_{22} = S_{20}$

$= S_{18} = S_{16} = S_{14} = S_{12} = S_{10} = S_{10} = S_{8} = S_{6} = S_{4} = S_{2} = 0$

(3) If $S_{36} = S_{39}$ = either S_{38} or S_{63} = 0, then $S_{31} = S_{35} = S_{37} = S_{42} = S_{38} = 0$

If $S_{29} = 0$, $S_{39} = 1$

If $S_{29} = 1$, $S_{39} = 0$

If $S_{39} = S_{35} = S_{31} = S_{37} = S_{38} = S_{42} = 0$, then $S_{36} = 0$

(4) If $S_{30} = 0$, $S_{57} = 1$

If $S_{30} = 1$, $S_{57} = 0$

If S_{61} = either S_{62} or $S_{58} = S_{57} = 0$; then $S_{59} = S_{60} = S_{56} = S_{58} = S_{32} = 0$

If $S_{56} = S_{57} = S_{60} = S_{32} = S_{59} = S_{58} = 0$; then $S_{61} = 0$

(5) If $S_{46} = 0$, then $S_{35} = S_{27} = S_{48} = S_{28} = S_{60} = 0$

If $S_{35} = S_{27} = S_{48} = S_{28} = S_{60} = 0$; then $S_{46} = 0$

(6) If $S_{47} = 0$, then $S_{42} = S_{56} = 0$

If $S_{42} = S_{56} = 0$, then $S_{47} = 0$

(7) If $S_{48} = S_{23}$ or $S_{25} = S_{26}$ or $S_{24} = S_{48} = S_{82} = 0$, then $S_{49} = S_{39} = S_{57} = 0$

TABLE B-I.- SWITCHING LOGIC FOR ALL NODES - Continued

Node

(8) If $S_{40} = 0$, then $S_1 = S_2 = 0$

If both $S_1 = 0$ and $S_2 = 0$, then $S_{40} = 0$

(9) If $S_4 = 1$, then $S_{B4} = 0$, and if $S_4 = 0$, then $S_{B4} = 1$

If $S_3 = 1$, then $S_{B3} = 0$, and if $S_3 = 0$, then $S_{B3} = 1$

If $S_{41} = 0$, then $S_3 = S_4 = 0$

If both $S_3 = 0$ and $S_4 = 0$, then $S_{41} = 0$

(10) If $S_{43} = 0$, $S_5 = S_6 = 0$

If both $S_5 = 0$ and $S_6 = 0$, then $S_{43} = 0$

(11) If $S_{44} = 0$, then $S_7 = S_8 = 0$

If both $S_7 = 0$ and $S_8 = 0$, then $S_{44} = 0$

(12) If $S_{45} = 0$, then $S_9 = S_{10} = 0$

If both $S_9 = 0$ and $S_{10} = 0$, then $S_{45} = 0$

(13) If $S_{83} = 0$, then $S_{11} = S_{12} = 0$

If both $S_{11} = 0$ and $S_{12} = 0$, then $S_{83} = 0$

(14) If $S_{50} = 0$, then $S_{13} = S_{14} = 0$

If both $S_{13} = 0$ and $S_{14} = 0$, then $S_{50} = 0$

(15) If $S_{52} = 0$, then $S_{15} = S_{16} = 0$

If both $S_{15} = 0$ and $S_{16} = 0$, then $S_{52} = 0$

(16) If $S_{53} = 0$, then $S_{17} = S_{18} = 0$

If both $S_{17} = 0$ and $S_{18} = 0$, then $S_{53} = 0$

(17) If $S_{54} = 0$, then $S_{19} = S_{20} = 0$

If both $S_{19} = 0$ and $S_{20} = 0$, then $S_{54} = 0$

TABLE B-I.- SWITCHING LOGIC FOR ALL NODES - Continued

Node

(18) If $S_{55} = 0$, then $S_{21} = S_{22} = 0$

If both $S_{21} = 0$ and $S_{22} = 0$, then $S_{55} = 0$

(19) If $S_{49} = S_{39} = S_{57} = 0$, then either S_{23} or S_{25} = either S_{26} or $S_{24} = S_{48} = S_{82} = 0$

(20) If $S_{65} = S_{66} = 0$, then $S_{64} = 0$
&
(23) If $S_{64} = 0$, then $S_{65} = S_{66} = 0$

If $S_{33} = S_{36} = S_{37} = S_{38} = S_{40} = S_{41} = S_{43} = S_{44} = S_{45} = S_{46} = S_{47} = S_{49} = S_{50} = S_{83}$

$= S_{51} = S_{52} = S_{53} = S_{54} = S_{55} = S_{58} = S_{59} = S_{61} = S_{34} = 0$, then $S_{64} = 0$

If $S_{65} = S_{66} = S_{73} = S_{74} = S_{75} = 0$, then $S_{67} = S_{68} = S_{78} = S_{77} = 0$

(21) If $S_{36} = S_{39} = S_{37} = S_{31} = S_{35} = S_{42} = 0$, then $S_{38} = 0$

If $S_{63} = S_{36} = S_{39} = 0$, then $S_{38} = 0$

(22) If $S_{61} = S_{59} = S_{32} = S_{60} = S_{57} = S_{56} = 0$, then $S_{58} = 0$

If $S_{62} = S_{61} = S_{57} = 0$, then $S_{58} = 0$

(23) See (20)

(24) If $S_{74} = 0$, then $S_{80} = S_{70} = 0$

If $S_{80} = S_{70} = 0$, then $S_{74} = 0$

(25) If $S_{75} = 0$, then $S_{81} = S_{71} = 0$

If $S_{81} = S_{71} = 0$, then $S_{75} = 0$

(26) If $S_{82} = 0$, then $S_{51} = 0$

If $S_{26} = 0$, then $S_{51} = 0$

(27) If $S_{66} = S_{77} = S_{78} = 0$, then $S_{79} = S_{80} = S_{81} = 0$

If $S_{79} = S_{80} = S_{81} = S_{66} = 0$, then $S_{77} = S_{78} = 0$

(28) If $S_{65} = S_{67} = S_{68} = 0$, then $S_{69} = S_{70} = S_{71} = 0$

If $S_{69} = S_{70} = S_{71} = S_{65} = 0$, then $S_{67} = S_{68} = 0$

TABLE B-I.- SWITCHING LOGIC FOR ALL NODES - Concluded

Node

(29) If $S_{72} = 0$, then $S_{68} = 0$

If $S_{68} = 0$, then $S_{72} = 0$

(30) If $S_{76} = 0$, then $S_{78} = 0$

If $S_{78} = 0$, then $S_{76} = 0$

(31) If $S_{73} = 0$, then $S_{69} = S_{79} = 0$

If $S_{69} = S_{79} = 0$, then $S_{73} = 0$

TABLE B-II.- EXAMPLES OF FIRST GUESS SWITCHING LOGIC

CSM switching constraints	Part no.	Load sharing configuration
$S_{27} = S_{28}$ either S_{29} or S_{31} = either S_{26} or S_{24} = either S_{23} or S_{25} = either S_{32} or $S_{30} = 0$ (Other switching is normal.)	1	R_3, R_5, R_{26}, R_6, and R_4 are to be shared equally by the number of entry and postlanding batteries that are on. R_{21} and R_{22} are the loads applied to the pyro batteries. If $S_{38} = S_{58} = 1$, then 1/3 of the load of both R_{21} and R_{22} is applied to the entry and postlanding batteries, the rest of the load is applied to the pyro batteries. If $S_{38} = S_{58} = 0$, the pyro batteries (if on) will carry loads R_{21} and R_{22}. The remaining loads are applied equally to the number of fuel cells on.
$S_{65} = S_{66} = S_{64} = 0$ (Other switching is normal.)	2	All CM loads are applied equally to the number of entry and postlanding batteries that are on. The constraint concerning loads R_{21} and R_{22}, as listed above, is to be observed when assigning loads to the pyro batteries. The SM loads are applied equally to the number of fuel cells on in the SM.
$S_{29} = S_{31} = S_{32} = 1$. Either S_{23} or $S_{25} = 0$ (Other switching is normal.)	3	Entry and postlandings batteries A and B (if they are on) are load sharing with the fuel cells. Assume that 30 percent of the load is applied equally to the two batteries and the remaining load is to be applied equally to the number of fuel cells on in the SM. A more accurate load sharing approximation will be determined by experimentation. Pyro batteries are treated the same as in part 1.
$S_{29} = S_{31} = S_{32} = S_{30} = S_{23} = S_{25} = 1$ (Other switching is normal.)	4	The same as in part 3 except that 30 percent of the total CSM load is to be applied equally to the three entry and postlanding batteries (if they are on).
$S_{29} = S_{31} = S_{57} = S_{23} = S_{25} = 1$. $S_{32} = S_{66}$ = either S_{26} or $S_{24} = 0$ (Other switching is normal.)	5	Same as part 4. (This is a simulation of CMBB bus loss.)
S_{65} = either S_{29} or S_{31} = either S_{23} or $S_{25} = 0$. $S_{32} = S_{30} = S_{26} = S_{24} = S_{35} = 1$ (Other switching is normal.)	6	Same as part 5. (This is a simulation of a CMBA bus loss.)

APPENDIX C

EPS CIRCUIT MATRIX EQUATIONS

APPENDIX C

EPS CIRCUIT MATRIX EQUATIONS

SYMBOLS

$E_{1, \ldots, 31}$	voltage at nodes 1, ..., 31
E_D	voltage drop across diode
R	bus connection equivalent resistance
R_D	diode equivalent resistance
S	switch
Z	variable load resistance

EQUATIONS

NODE 1:

$$- I_1 - I_4 - I_7 - I_{10} - I_{13} - I_{16} - I_{19} - I_{21} - I_{24} - I_{27} - I_{30} + I_{33} - I_{36}$$

$$+ I_{38} - I_{41} + I_{61} = 0$$

$$- \frac{(E_1 \quad E_8 \quad E_{D1})}{R_1 + R_{D1}} S_1 - \frac{(E_1 - E_9 - E_{D2}) S_3 S_{B4}}{R_2 + R_{D2}} - \frac{(E_1 - E_{10} - E_{D3}) S_5}{R_3 + R_{D3}}$$

$$- \frac{(E_1 - E_{11} - E_{D4}) S_7}{R_4 + R_{D4}} - \frac{(E_1 - E_{12} - E_{D5}) S_9}{R_5 + R_{D5}} - \frac{(E_1 - E_{13} - E_{D6}) S_{11}}{R_6 + R_{D6}}$$

$$- \frac{(E_1 - E_{14} - E_{D7}) S_{13}}{R_7 + R_{D7}} - \frac{(E_1 - E_{15} - E_{D8}) S_{15}}{R_8 + R_{D8}} - \frac{(E_1 - E_{16} - E_{D9}) S_{17}}{R_9 + R_{D9}}$$

$$- \frac{(E_1 - E_{17} - E_{D10}) S_{19}}{R_{10} + R_{D10}} - \frac{(E_1 - E_{18} - E_{D11}) S_{21}}{R_{11} + R_{D11}} + \frac{(E_{19} - E_1 - E_{D12}) S_{23} S_{25}}{R_{12} + R_{D12}}$$

$$- \frac{(E_1 - E_5 - E_{D13}) S_{27}}{R_{13} + R_{D13}} + \frac{(E_3 - E_1 - E_{D16}) S_{29} S_{31}}{R_{15} + R_{D16}} - \frac{(E_1 - E_{23}) S_{33}}{Z_1}$$

$$+ \frac{(E_{28} - E_1) S_{65}}{R_{55}} = 0$$

$$\text{Batt }(1, 1) = -\frac{S_1}{R_1 + R_{D1}} - \frac{S_3\ S_{B4}}{R_2 + R_{D2}} - \frac{S_5}{R_3 + R_{D3}} - \frac{S_7}{R_4 + R_{D4}} - \frac{S_9}{R_5 + R_{D5}} - \frac{S_{11}}{R_6 + R_{D6}}$$

$$- \frac{S_{13}}{R_7 + R_{D7}} - \frac{S_{15}}{R_8 + R_{D8}} - \frac{S_{17}}{R_9 + R_{D9}} - \frac{S_{19}}{R_{10} + R_{D10}} - \frac{S_{21}}{R_{11} + R_{D11}}$$

$$- \frac{S_{23}\ S_{25}}{R_{12} + R_{D12}} - \frac{S_{27}}{R_{13} + R_{D13}} - \frac{S_{29}\ S_{31}}{R_{15} + R_{D16}} - \frac{S_{33}}{Z_1} - \frac{S_{65}}{R_{55}}$$

$$\text{Batt }(1, 3) = \frac{S_{29}\ S_{31}}{R_{15} + R_{D16}}$$

$$\text{Batt }(1, 5) = \frac{S_{27}}{R_{13} + R_{D13}}$$

$$\text{Batt }(1, 8) = \frac{S_1}{R_1 + R_{D1}}$$

$$\text{Batt }(1, 9) = \frac{S_3\ S_{B4}}{R_2 + R_{D2}}$$

$$\text{Batt }(1, 10) = \frac{S_5}{R_3 + R_{D3}}$$

$$\text{Batt }(1, 11) = \frac{S_7}{R_4 + R_{D4}}$$

$$\text{Batt }(1, 12) = \frac{S_9}{R_5 + R_{D5}}$$

$$\text{Batt }(1, 13) = \frac{S_{11}}{R_6 + R_{D6}}$$

$$\text{Batt }(1, 14) = \frac{S_{13}}{R_7 + R_{D7}}$$

$$\text{Batt }(1, 15) = \frac{S_{15}}{R_8 + R_{D8}}$$

$$\text{Batt }(1, 16) = \frac{S_{17}}{R_9 + R_{D9}}$$

$$\text{Batt }(1, 17) = \frac{S_{19}}{R_{10} + R_{D10}}$$

$$\text{Batt }(1, 18) = \frac{S_{21}}{R_{11} + R_{D11}}$$

$$\text{Batt }(1, 19) = \frac{S_{23}\, S_{25}}{R_{12} + R_{D12}}$$

$$\text{Batt }(1, 23) = \frac{S_{33}}{Z_1}$$

$$\text{Batt }(1, 28) = \frac{S_{65}}{R_{55}}$$

$$\begin{aligned}\text{Batt }(1, 32) = &- \text{Batt }(1, 8)\, E_{D1} - \text{Batt }(1, 9)\, E_{D2} - \text{Batt }(1, 10)\, E_{D3} - \text{Batt }(1, 11)\, E_{D4} \\ &- \text{Batt }(1, 12)\, E_{D5} - \text{Batt }(1, 13)\, E_{D6} - \text{Batt }(1, 14)\, E_{D7} \\ &- \text{Batt }(1, 15)\, E_{D8} - \text{Batt }(1, 16)\, E_{D9} - \text{Batt }(1, 17)\, E_{D10} \\ &- \text{Batt }(1, 18)\, E_{D11} + \text{Batt }(1, 19)\, E_{D12} - \text{Batt }(1, 5)\, E_{D13} \\ &+ \text{Batt }(1, 3)\, E_{D16}\end{aligned}$$

NODE 2:

$$- \frac{(E_2 - E_8 - E_{D36})\, S_2}{R_{50} + R_{D36}} - \frac{(E_2 - E_9 - E_{D35})\, S_4\, S_{B3}}{R_{49} + R_{D35}} - \frac{(E_2 - E_{10} - E_{D34})\, S_6}{R_{48} + R_{D34}}$$

$$- \frac{(E_2 - E_{11} - E_{D33})\, S_8}{R_{47} + R_{D33}} - \frac{(E_2 - E_{12} - E_{D32})\, S_{10}}{R_{46} + R_{D32}} - \frac{(E_2 - E_{13} - E_{D31})\, S_{12}}{R_{45} + R_{D31}}$$

$$- \frac{(E_2 - E_{14} - E_{D30})\, S_{14}}{R_{44} + R_{D30}} - \frac{(E_2 - E_{15} - E_{D29})\, S_{16}}{R_{43} + R_{D29}} - \frac{(E_2 - E_{16} - E_{D28})\, S_{18}}{R_{42} + R_{D28}}$$

$$- \frac{(E_2 - E_{17} - E_{D27})\, S_{20}}{R_{41} + R_{D27}} - \frac{(E_2 - E_{18} - E_{D26})\, S_{22}}{R_{40} + R_{D26}} + \frac{(E_{19} - E_2 - E_{D25})\, S_{26}\, S_{24}}{R_{39} + R_{D25}}$$

$$- \frac{(E_2 - E_5 - E_{D24})\, S_{28}}{R_{38} + R_{D24}} + \frac{(E_4 - E_2 - E_{D23})\, S_{32}\, S_{30}}{R_{37} + R_{D23}} - \frac{(E_2 - E_{23})\, S_{34}}{Z_2}$$

$$\cancel{+ \frac{(E_{27} - E_2)\, S_{66}}{R_{56}} = 0}$$

$$\text{Batt }(2,\ 2) = - \frac{S_2}{R_{50} + R_{D36}} - \frac{S_4\, S_{B3}}{R_{49} + R_{D35}} - \frac{S_6}{R_{48} + R_{D34}} - \frac{S_8}{R_{47} + R_{D33}} - \frac{S_{10}}{R_{46} + R_{D32}}$$

$$- \frac{S_{12}}{R_{45} + R_{D31}} - \frac{S_{14}}{R_{44} + R_{D30}} - \frac{S_{16}}{R_{43} + R_{D29}} - \frac{S_{18}}{R_{42} + R_{D28}} - \frac{S_{20}}{R_{41} + R_{D27}}$$

$$- \frac{S_{22}}{R_{40} + R_{D26}} - \frac{S_{26}\, S_{24}}{R_{39} + R_{D25}} - \frac{S_{28}}{R_{38} + R_{D24}} - \frac{S_{32}\, S_{30}}{R_{37} + R_{D23}} - \frac{S_{34}}{Z_2} - \frac{S_{66}}{R_{56}}$$

$$\text{Batt }(2,\ 4) = \frac{S_{32}\, S_{30}}{R_{37} + R_{D23}}$$

$$\text{Batt }(2,\ 5) = \frac{S_{28}}{R_{38} + R_{D24}}$$

$$\text{Batt }(2,\ 8) = \frac{S_2}{R_{50} + R_{D36}}$$

$$\mathrm{Batt}\ (2,\ 9) = \frac{S_4\ S_{B3}}{R_{49} + R_{D35}}$$

$$\mathrm{Batt}\ (2,\ 10) = \frac{S_6}{R_{48} + R_{D34}}$$

$$\mathrm{Batt}\ (2,\ 11) = \frac{S_8}{R_{47} + R_{D33}}$$

$$\mathrm{Batt}\ (2,\ 12) = \frac{S_{10}}{R_{46} + R_{D32}}$$

$$\mathrm{Batt}\ (2,\ 13) = \frac{S_{12}}{R_{45} + R_{D31}}$$

$$\mathrm{Batt}\ (2,\ 14) = \frac{S_{14}}{R_{44} + R_{D30}}$$

$$\mathrm{Batt}\ (2,\ 15) = \frac{S_{16}}{R_{43} + R_{D29}}$$

$$\mathrm{Batt}\ (2,\ 16) = \frac{S_{18}}{R_{42} + R_{D28}}$$

$$\mathrm{Batt}\ (2,\ 17) = \frac{S_{20}}{R_{41} + R_{D27}}$$

$$\mathrm{Batt}\ (2,\ 18) = \frac{S_{22}}{R_{40} + R_{D26}}$$

$$\mathrm{Batt}\ (2,\ 19) = \frac{S_{26}\ S_{24}}{R_{39} + R_{D25}}$$

$$\mathrm{Batt}\ (2,\ 23) = \frac{S_{34}}{Z_2}$$

$$\mathrm{Batt}\ (2,\ 27) = \frac{S_{66}}{R_{56}}$$

$$
\begin{aligned}
\mathrm{Batt}\ (2,\ 32) = &- \mathrm{Batt}\ (2,\ 8)\ E_{D36} - \mathrm{Batt}\ (2,\ 9)\ E_{D35} - \mathrm{Batt}\ (2,\ 10)\ E_{D34} \\
&- \mathrm{Batt}\ (2,\ 11)\ E_{D33} - \mathrm{Batt}\ (2,\ 12)\ E_{D32} - \mathrm{Batt}\ (2,\ 13)\ E_{D31} \\
&- \mathrm{Batt}\ (2,\ 14)\ E_{D30} - \mathrm{Batt}\ (2,\ 15)\ E_{D29} - \mathrm{Batt}\ (2,\ 16)\ E_{D28} \\
&- \mathrm{Batt}\ (2,\ 17)\ E_{D27} - \mathrm{Batt}\ (2,\ 18)\ E_{D26} + \mathrm{Batt}\ (2,\ 19)\ E_{D25} \\
&- \mathrm{Batt}\ (2,\ 5)\ E_{D24} + \mathrm{Batt}\ (2,\ 4)\ E_{D23}
\end{aligned}
$$

NODE 3:

$$I_{43} - I_{38} - I_{42} - I_{46} - I_{47} - I_{45} - I_{44} = 0$$

$$\frac{(E_{23} - E_3 + E_{BA})\, S_{36}}{R_{17} + R_{18}} - \frac{(E_3 - E_1 - E_{D16})\, S_{29}\, S_{31}}{R_{15} + R_{D16}} - \frac{(E_3 - E_5 - E_{D14} - E_{D15})\, S_{35}}{R_{14} + R_{D15} + R_{D14}}$$

$$- \frac{(E_3 - E_7)\, S_{39}}{R_{16}} - \frac{(E_3 - E_6 - E_{D17})\, S_{42}}{R_{22} + R_{17}} - \frac{(E_3 - E_{21})\, S_{38}}{R_{19}} - \frac{(E_3 - E_{23})\, S_{37}}{Z_3} = 0$$

$$\text{Batt}\,(3,\,3) = \frac{S_{36}}{R_{17} + R_{18}} - \frac{S_{29}\, S_{31}}{R_{15} + R_{D16}} - \frac{S_{35}}{R_{14} + R_{D15} + R_{D14}} - \frac{S_{39}}{R_{16}} - \frac{S_{42}}{R_{22} + R_{17}}$$

$$- \frac{S_{38}}{R_{19}} - \frac{S_{37}}{Z_3}$$

Batt (3, 1) = Batt (1, 3)

$$\text{Batt}\,(3,\,23) = \frac{S_{36}}{R_{17} + R_{18}} + \frac{S_{37}}{Z_3}$$

$$\text{Batt}\,(3,\,5) = \frac{S_{35}}{R_{14} + R_{D15} + R_{D14}}$$

$$\text{Batt}\,(3,\,7) = \frac{S_{39}}{R_{16}}$$

$$\text{Batt}\,(3,\,6) = \frac{S_{42}}{R_{22} + R_{17}}$$

$$\text{Batt}\,(3,\,21) = \frac{S_{38}}{R_{19}}$$

$$\text{Batt}\,(3,\,32) = - \frac{S_{36}}{R_{17} + R_{18}}\,(E_{BA}) - \text{Batt}\,(3,\,1)\, E_{D16} - \text{Batt}\,(3,\,5)\,(E_{D14} + E_{D15})$$

$$- \text{Batt}\,(3,\,6)\, ED_{17}$$

NODE 4:

$$I_{56} - I_{39} - I_{49} - I_{50} - I_{51} - I_{54} - I_{55} = 0$$

$$\frac{(E_{23} + E_{BB} - E_4)\, S_{61}}{R_{35} + R_{36}} - \frac{(E_4 - E_2 - E_{D23})\, S_{32}\, S_{30}}{R_{37} + R_{D23}} - \frac{(E_4 - E_5 - E_{D21} - E_{D22})\, S_{60}}{R_{30} + R_{D21} + R_{D22}}$$

$$- \frac{(E_4 - E_7)\, S_{57}}{R_{29}} - \frac{(E_4 - E_6 - E_{D20})\, S_{56}}{R_{28} + R_{D20}} - \frac{(E_4 - E_{22})\, S_{58}}{R_{31}} - \frac{(E_4 - E_{23})\, S_{59}}{Z_4} = 0$$

$$\text{Batt }(4,\ 4) = - \frac{S_{61}}{R_{35} + R_{36}} - \frac{S_{32}\, S_{30}}{R_{37} + R_{D23}} - \frac{S_{60}}{R_{30} + R_{D21} + R_{D22}} - \frac{S_{56}}{R_{28} + R_{D20}} - \frac{S_{58}}{R_{31}}$$

$$- \frac{S_{59}}{Z_4}$$

$$\cancel{\text{Batt }(4,\ 23) =} \frac{S_{61}}{R_{35} + R_{36}} + \frac{S_{59}}{Z_4} = 0$$

$$\text{Batt }(4,\ 2) = \frac{S_{32}\, S_{30}}{R_{37} + R_{D23}}$$

$$\text{Batt }(4,\ 5) = \frac{S_{60}}{R_{30} + R_{D21} + R_{D22}}$$

$$\text{Batt }(4,\ 7) = \frac{S_{57}}{R_{29}}$$

$$\text{Batt }(4,\ 6) = \frac{S_{56}}{R_{28} + R_{D20}}$$

$$\text{Batt }(4,\ 22) = \frac{S_{58}}{R_{31}}$$

$$\text{Batt }(4,\ 32) = - \frac{S_{61}}{R_{35} + R_{36}}\ (E_{BB}) - \text{Batt }(4,\ 2)\ E_{D23} - \text{Batt }(4,\ 5)\ (E_{D21} + E_{D22})$$

$$- \text{Batt }(4,\ 6)\ E_{D20}$$

NODE 5:

$$I_{42} + I_{36} + I_{48} + I_{49} + I_{37} - I_{57} = 0$$

$$\frac{(E_3 - E_5 - E_{D14} - E_{D15})\ S_{35}}{R_{14} + R_{D14} + R_{D15}} + \frac{(E_1 - E_5 - E_{D13})\ S_{27}}{R_{13} + R_{D13}} + \frac{(E_{19} - E_5 - E_{D18} - E_{D19})\ S_{48}}{R_{23} + R_{D18} + R_{D19}}$$

$$+ \frac{(E_4 - E_5 - E_{D21} - E_{D22})\ S_{60}}{R_{30} + R_{D21} + R_{D22}} + \frac{(E_2 - E_5 - E_{D24})\ S_{28}}{R_{38} + R_{D24}} - \frac{(E_5 - E_{23})\ S_{46}}{Z_5}$$

$$\text{Batt }(5,\ 5) = - \frac{S_{35}}{R_{14} + R_{D14} + R_{D15}} - \frac{S_{60}}{R_{30} + R_{D21} + R_{D22}} - \frac{S_{28}}{R_{38} + R_{D24}} - \frac{S_{27}}{R_{13} + R_{D13}}$$

$$- \frac{S_{48}}{R_{23} + R_{D18} + R_{D19}} - \frac{S_{46}}{Z_5}$$

$$\text{Batt }(5,\ 19) = \frac{S_{48}}{R_{23} + R_{D18} + R_{D19}}$$

Batt (5, 4) = Batt (4, 5

Batt (5, 1) = Batt (1, 5)

Batt (5, 3) = Batt (3, 5)

Batt (5, 2) = Batt (2, 5)

$$\text{Batt }(5,\ 23) = \frac{S_{46}}{Z_5}$$

$$\text{Batt }(5,\ 32) = \text{Batt }(5,\ 3)\ (E_{D14} + E_{D15}) + \text{Batt }(5,\ 1)\ E_{D13} + \text{Batt }(5,\ 19)\ (E_{D18} + E_{D19})$$

$$+ \text{Batt }(5,\ 4)\ (E_{D21} + E_{D22}) + \text{Batt }(5,\ 2)\ E_{D24}$$

NODE 6:

$$I_{47} - I_{58} + I_{51} = 0$$

$$\frac{(E_3 - E_6 - E_{D17})\, S_{42}}{R_{22} + R_{D17}} - \frac{(E_6 - E_{23})\, S_{47}}{Z_6} + \frac{(E_4 - E_6 - E_{D20})\, S_{56}}{R_{28} + R_{D20}} = 0$$

Batt (6, 3) = Batt (3, 6)

Batt (6, 4) = Batt (4, 6)

$$\text{Batt}\ (6,\ 23) = \frac{S_{47}}{Z_6}$$

$$\text{Batt}\ (6,\ 6) = -\frac{S_{42}}{R_{22} + R_{D17}} - \frac{S_{47}}{Z_6} - \frac{S_{56}}{R_{28} + R_{D20}}$$

$$\text{Batt}\ (6,\ 32) = +\ \text{Batt}\ (6,\ 3)\ E_{D17} + \text{Batt}\ (6,\ 4)\ E_{D20}$$

NODE 7:

$$I_{46} + I_{50} - I_{34} + I_{76} - I_{52} = 0$$

ST = 1.0

If either S_{25} or S_{23} = either S_{26} or S_{24} = S_{48} = 0
then ST = 0

$$\frac{(E_3 - E_7)\, S_{39}}{R_{16}} + \frac{(E_4 - E_7)\, S_{57}}{R_{29}} - \frac{(E_7 - E_{19})\, ST}{R_{24}} + \frac{(E_{23} + E_{BC} - E_7)\, S_{49}}{R_{26} + R_{27}}$$

$$- \frac{(E_7 - E_{26})\, S_{82}}{R_{25}} = 0$$

Batt (7, 3) = Batt (3, 7)

Batt (7, 4) = Batt (4, 7)

Batt (7, 19) = $\frac{ST}{R_{24}}$

Batt (7, 23) = $\frac{S_{49}}{R_{26} + R_{27}}$

Batt (7, 7) = - Batt (7, 3) - Batt (7, 4) - Batt (7, 19) - Batt (7, 23) - Batt (7, 26)

Batt (7, 32) = - Batt (7, 23) E_{BC}

Batt (7, 26) = $\frac{S_{82}}{R_{25}}$

NODE 8:

$$I_1 + I_2 - I_3 = 0$$

$$\frac{(E_1 - E_8 - E_{D1})\ S_1}{R_1 + R_{D1}} + \frac{(E_2 - E_8 - E_{D36})\ S_2}{R_{50} + R_{D36}} - \frac{(E_8 - E_{23})\ S_{40}}{Z_8} = 0$$

Batt (8, 1) = Batt (1, 8)

Batt (8, 2) = Batt (2, 8)

Batt (8, 23) = $\dfrac{S_{40}}{Z_8}$

Batt (8, 8) = - Batt (8, 1) - Batt (8, 2) - Batt (8, 23)

Batt (8, 32) = Batt (8, 1) E_{D1} + Batt (8, 2) E_{D36}

NODE 9:

$$I_4 + I_5 - I_6 = 0$$

$$\frac{(E_1 - E_9 - E_{D2})\, S_3\, S_{B4}}{R_2 + R_{D2}} + \frac{(E_2 - E_9 - E_{D35})\, S_{B3}\, S_4}{R_{49} + R_{D35}} - \frac{(E_9 - E_{23})\, S_{41}}{Z_9} = 0$$

Batt (9, 1) = Batt (1, 9)

Batt (9, 2) = Batt (2, 9)

$$\text{Batt}\ (9,\ 23) = \frac{S_{41}}{Z_9}$$

Batt (9, 9) = - Batt (9, 1) - Batt (9, 2) - Batt (9, 23)

Batt (9, 32) = Batt (9, 1) E_{D2} + Batt (9, 2) E_{D35}

NODE 10:

$$I_7 + I_8 - I_9 = 0$$

$$\frac{(E_1 - E_{10} - E_{D3})\, S_5}{R_3 + R_{D3}} + \frac{(E_2 - E_{10} - E_{D34})\, S_6}{R_{48} + R_{D34}} - \frac{(E_{10} - E_{23})\, S_{43}}{Z_{10}} = 0$$

Batt (10, 1) = Batt (1, 10)

Batt (10, 2) = Batt (2, 10)

Batt (10, 23) = $\frac{S_{43}}{Z_{10}}$

Batt (10, 10) = - Batt (10, 1) - Batt (10, 2) - Batt (10, 23)

Batt (10, 32) = Batt (10, 1) E_{D3} + Batt (10, 2) E_{D34}

NODE 11:

$$I_{10} + I_{11} - I_{12} = 0$$

$$\frac{(E_1 - E_{11} - E_{D4})\ S_7}{R_4 + R_{D4}} + \frac{(E_2 - E_{11} - E_{D33})\ S_8}{R_{47} + R_{D33}} - \frac{(E_{11} - E_{23})\ S_{44}}{Z_{11}} = 0$$

Batt (11, 1) = Batt (1, 11)

Batt (11, 2) = Batt (2, 11)

$$\text{Batt (11, 23)} = \frac{S_{44}}{Z_{11}}$$

Batt (11, 11) = - Batt (11, 1) - Batt (11, 2) - Batt (11, 23)

Batt (11, 32) = Batt (11, 1) E_{D4} + Batt (11, 2) E_{D33}

NODE 12:

$$I_{13} + I_{15} - I_{14} = 0$$

$$\frac{(E_1 - E_{12} - E_{D5})\ S_9}{R_5 + R_{D5}} + \frac{(E_2 - E_{12} - E_{D32})\ S_{10}}{R_{46} + R_{D32}} - \frac{(E_{12} - E_{23})\ S_{45}}{Z_{12}} = 0$$

Batt (12, 1) = Batt (1, 12)

Batt (12, 2) = Batt (2, 12)

Batt (12, 23) = $\frac{S_{45}}{Z_{12}}$

Batt (12, 12) = - Batt (12, 1) - Batt (12, 2) - Batt (12, 23)

Batt (12, 32) = Batt (12, 1) E_{D5} + Batt (12, 2) E_{D32}

NODE 13:

$$I_{16} + I_{17} - I_{18} = 0$$

$$\frac{(E_1 - E_{13} - E_{D6})\, S_{11}}{R_6 + R_{D6}} + \frac{(E_2 - E_{13} - E_{D31})\, S_{12}}{R_{45} + R_{D31}} - \frac{(E_{1e} - E_{23})\, S_{83}}{Z_{13}} = 0$$

Batt (13, 1) = Batt (1, 13)

Batt (13, 2) = Batt (2, 13)

$$\text{Batt}\ (13,\ 23) = \frac{S_{83}}{Z_{13}}$$

Batt (13, 13) = -Batt (13, 1) - Batt (13, 2) - Batt (13, 23)

Batt (13, 32) = Batt (13, 1) E_{D6} + Batt (13, 2) E_{D31}

NODE 14:

$$I_{19} + I_{77} - I_{20} = 0$$

$$\frac{(E_1 - E_{14} - E_{D7})\ S_{13}}{R_7 + R_{D7}} + \frac{(E_2 - E_{14} - E_{D30})\ S_{14}}{R_{44} + R_{D30}} - \frac{(E_{14} - E_{23})\ S_{50}}{Z_{14}} = 0$$

Batt (14, 1) = Batt (1, 14)

Batt (14, 2) = Batt (2, 14)

$$\text{Batt } (14,\ 23) = \frac{S_{50}}{Z_{14}}$$

$$\text{Batt } (14,\ 32) = \text{Batt } (14,\ 1)\ E_{D7} + \text{Batt } (14,\ 2)\ E_{D30}$$

Batt (14, 14) = -Batt (14, 1) - Batt (14, 2) - Batt (14, 23)

NODE 15:

$I_{21} + I_{22} - I_{23} = 0$

$$\frac{(E_1 - E_{15} - E_{D8})\ S_{15}}{R_8 + R_{D8}} + \frac{(E_2 - E_{15} - E_{D29})\ S_{16}}{R_{43} + R_{D29}} - \frac{(E_{15} - E_{23})\ S_{52}}{Z_{15}} = 0$$

Batt (15, 1) = Batt (1, 15)

Batt (15, 2) = Batt (2, 15)

Batt (15, 23) = $\frac{S_{52}}{Z_{15}}$

Batt (15, 15) = - Batt (1, 15) - Batt (2, 15) - Batt (15, 23)

Batt (15, 32) = Batt (15, 1) E_{D8} + Batt (15, 2) E_{D29}

NODE 16:

$$I_{24} + I_{25} - I_{26} = 0$$

$$\frac{(E_1 - E_{16} - E_{D9})\, S_{17}}{R_9 + R_{D9}} + \frac{(E_2 - E_{16} - E_{D28})\, S_{18}}{R_{42} + R_{D28}} - \frac{(E_{16} - E_{23})\, S_{53}}{Z_{16}} = 0$$

Batt (16, 1) = Batt (1, 16)

Batt (16, 2) = Batt (2, 16)

$$\text{Batt } (16,\ 23) = \frac{S_{53}}{Z_{16}}$$

Batt (16, 16) = - Batt (1, 16) - Batt (2, 16) - Batt (16, 23)

Batt (16, 32) = Batt (16, 1) E_{D9} + Batt (16, 2) E_{D28}

NODE 17:

$$I_{27} + I_{29} - I_{28} = 0$$

$$\frac{(E_1 - E_{17} - E_{D10})\ S_{19}}{R_{18} + R_{D10}} + \frac{(E_2 - E_{17} - E_{D27})\ S_{20}}{R_{41} + R_{D27}} - \frac{(E_{17} - E_{23})\ S_{54}}{Z_{17}} = 0$$

Batt (17, 1) = Batt (1, 17)

Batt (17, 2) = Batt (2, 17)

Batt (17, 23) = $\frac{S_{54}}{Z_{17}}$

Batt (17, 17) = - Batt (17, 1) - Batt (17, 2) - Batt (17, 23)

Batt (17, 32) = Batt (17, 1) E_{D10} + Batt (17, 2) E_{D27}

NODE 18:

$$I_{30} + I_{32} - I_{31} = 0$$

$$\frac{(E_1 - E_{18} - E_{D11})\, S_{21}}{R_{11} + R_{D11}} + \frac{(E_2 - E_{18} - E_{D26})\, S_{22}}{R_{40} + R_{D26}} - \frac{(E_{18} - E_{23})\, S_{55}}{Z_{18}} = 0$$

Batt (18, 1) = Batt (1, 18)

Batt (18, 2) = Batt (2, 18)

Batt (18, 23) = $\frac{S_{55}}{Z_{18}}$

Batt (18, 18) = - Batt (18, 1) - Batt (18, 2) - Batt (18, 23)

Batt (18, 32) = Batt (18, 1) E_{D11} + Batt (18, 2) E_{D26}

NODE 19:

$$-I_{33} - I_{35} - I_{48} + I_{34} = 0$$

$$-\frac{(E_{19} - E_1 - E_{D12})\, S_{23}\, S_{25}}{R_{12} + R_{D12}} - \frac{(E_{19} - E_2 - E_{D25})\, S_{26}\, S_{24}}{R_{39} + R_{D25}} + \frac{(E_7 - E_{19})\, ST}{R_{24}}$$

$$-\frac{(E_{19} - E_5 - E_{D18} - E_{D19})\, S_{48}}{R_{23} + R_{D18} + R_{D19}} = 0$$

Batt (19, 1) = Batt (1, 19)

Batt (19, 2) = Batt (2, 19)

Batt (19, 7) = Batt (7, 19)

Batt (19, 5) = Batt (5, 19)

Batt (19, 19) = - Batt (19, 1) - Batt (19, 2) - Batt (19, 7) - Batt (19, 5)

Batt (19, 32) = - Batt (19, 1) E_{D12} - Batt (19, 2) E_{D25} - Batt (19, 5) (E_{D18} + E_{D19})

NODE 20:

$$I_{59} + I_{62} + I_{67} - I_{75} - I_{74} - I_{73} + I_{78} + I_{79} = 0$$

$$- \frac{(E_{20} + E_{FC3} - E_{25})\, S_{75}}{R_{66} + R_{67}} - \frac{(E_{20} + E_{FC2} - E_{24})\, S_{74}}{R_{68} + R_{52}} - \frac{(E_{20} + E_{FC1} - E_{31})\, S_{73}}{R_{53} + R_{54}}$$

$$+ \frac{(E_{29} - E_{20})\, S_{72}}{Z_{29} + R_{34}} + \frac{(E_{30} - E_{20})\, S_{76}}{Z_{30} + R_{65}} + \frac{(E_{23} - E_{20})\, S_{64}}{R_{51}} + \frac{(E_{28} - E_{20})\, S_{67}}{Z_{28}}$$

$$+ \frac{(E_{27} - E_{20})\, S_{77}}{Z_{27}} = 0$$

$$\text{Batt}\ (20,\ 23) = \frac{S_{64}}{R_{51}}$$

$$\text{Batt}\ (20,\ 28) = \frac{S_{67}}{Z_{28}}$$

$$\text{Batt}\ (20,\ 27) = \frac{S_{77}}{Z_{27}}$$

$$\text{Batt}\ (20,\ 25) = \frac{S_{75}}{R_{66} + R_{67}}$$

$$\text{Batt}\ (20,\ 24) = \frac{S_{74}}{R_{68} + R_{52}}$$

$$\text{Batt}\ (20,\ 31) = \frac{S_{73}}{R_{53} + R_{54}}$$

$$\text{Batt}\ (20,\ 29) = \frac{S_{72}}{Z_{29} + R_{34}}$$

$$\text{Batt}\ (20,\ 30) = \frac{S_{76}}{Z_{30} + R_{65}}$$

$$\mathrm{Batt}\ (20,\ 20) = -\ \mathrm{Batt}\ (20,\ 23) - \mathrm{Batt}\ (20,\ 28) - \mathrm{Batt}\ (20,\ 27) - \mathrm{Batt}\ (20,\ 25)$$

$$-\ \mathrm{Batt}\ (20,\ 24) - \mathrm{Batt}\ (20,\ 31) - \mathrm{Batt}\ (20,\ 29) - \mathrm{Batt}\ (20,\ 30)$$

$$\mathrm{Batt}\ (20,\ 32) = \mathrm{Batt}\ (20,\ 25)\ E_{FC3} + \mathrm{Batt}\ (20,\ 24)\ E_{FC2} + \mathrm{Batt}\ (20,\ 31)\ E_{FC1}$$

NODE 21:

$$I_{45} + I_{80} - I_{81} = 0$$

ST = 1.0

If $S_{38} = 0$ and $S_{63} = 0$

then ST = 0

$$\frac{(E_3 - E_{21})\, S_{38}}{R_{19}} + \frac{(E_{23} - E_{21} + E_{PBA})\, S_{63}}{R_{20} + R_{21}} - \frac{(E_{21} - E_{23})\, ST}{Z_{21}} = 0$$

Batt (21, 3) = Batt (3, 21)

$$\text{Batt }(21,\ 23) = \frac{S_{63}}{R_{20} + R_{21}} + \frac{ST}{Z_{21}}$$

Batt (21, 21) = - Batt (21, 3) - Batt (21, 23)

$$\text{Batt }(21,\ 32) = -\frac{S_{63}}{R_{20} + R_{21}} (E_{PBA})$$

NODE 22:

$$I_{54} - I_{82} + I_{83} = 0$$

ST = 1.0

If $S_{62} = S_{58} = 0$

then ST = 0

$$\frac{(E_4 - E_{22})\, S_{58}}{R_{31}} - \frac{(E_{22} - E_{23})\, ST}{Z_{22}} + \frac{(E_{23} - E_{22} + E_{PBB})\, S_{62}}{R_{33} + R_{32}} = 0$$

Batt (22, 4) = Batt (4, 22)

$$\text{Batt } (22, 23) = \frac{ST}{Z_{22}} + \frac{S_{62}}{R_{33} + R_{22}}$$

Batt (22, 22) = - Batt (22, 4) - Batt (22, 23)

$$\text{Batt } (22, 32) = \frac{S_{62}}{R_{33} + R_{32}} (E_{PBB})$$

Node 23:

$$I_{41} - I_{43} + I_{44} + I_{81} + I_{80} + I_3 + I_6 + I_9 + I_{12} + I_{14} + I_{57} + I_{58} - I_{76} + I_{18}$$
$$+ I_{20} + I_{53} + I_{23} + I_{26} + I_{28} + I_{31} - I_{83} + I_{82} + I_{55} + I_{56} + I_{40} - I_{59} = 0$$

$$\frac{(E_1 - E_{23})\ S_{33}}{Z_1} - \frac{(E_{23} - E_3 + E_{BA})\ S_{36}}{R_{17} + R_{18}} + \frac{(E_3 - E_{23})\ S_{37}}{Z_3} + \frac{(E_{21} - E_{23})}{Z_{21}}$$
$$+ \frac{(E_{23} - E_{21} + E_{PBA})\ S_{63}}{R_{21} + R_{20}} + \frac{(E_8 - E_{23})\ S_{40}}{Z_8} + \frac{(E_9 - E_{23})\ S_{41}}{Z_9} + \frac{(E_{10} - E_{23})\ S_{43}}{Z_{10}}$$
$$+ \frac{(E_{11} - E_{23})\ S_{44}}{Z_{11}} + \frac{(E_{12} - E_{23})\ S_{45}}{Z_{12}} + \frac{(E_5 - E_{23})\ S_{46}}{Z_5} + \frac{(E_6 - E_{23})\ S_{47}}{Z_6}$$
$$- \frac{(E_{23} + E_{BC} - E_7)\ S_{49}}{R_{26} + R_{27}} + \frac{(E_{13} - E_{23})\ S_{83}}{Z_{13}} + \frac{(E_{14} - E_{23})\ S_{50}}{Z_{14}} + \frac{(E_{26} - E_{23})\ S_{51}}{Z_{26}}$$
$$+ \frac{(E_{15} - E_{23})\ S_{52}}{Z_{15}} + \frac{(E_{16} - E_{23})\ S_{53}}{Z_{16}} + \frac{(E_{17} - E_{23})\ S_{54}}{Z_{17}} + \frac{(E_{18} - E_{23})\ S_{55}}{Z_{18}}$$
$$- \frac{(E_{23} + E_{PBB} - E_{22})\ S_{62}}{R_{32} + R_{33}} + \frac{(E_{22} - E_{23})}{Z_{22}} + \frac{(E_4 - E_{23})\ S_{59}}{Z_4} - \frac{(E_{23} - E_4 + E_{BB})\ S_{61}}{R_{35} + R_{36}}$$
$$+ \frac{(E_2 - E_{23})\ S_{34}}{Z_2} - \frac{(E_{23} - E_{20})\ S_{64}}{R_{51}} = 0$$

ST = 1.0

If $S_{38} = S_{63} = 0$

Then ST = 0

Batt (23, 21) = Batt (21, 23)

Batt (23, 8) = Batt (8, 23)

Batt (23, 9) = Batt (9, 23)

Batt (23, 10) = Batt (10, 23)

Batt (23, 11) = Batt (11, 23)

Batt (23, 12) = Batt (12, 23)

Batt (23, 5) = Batt (5, 23)

Batt (23, 6) = Batt (6, 23)

Batt (23, 7) = Batt (7, 23)

Batt (23, 13) = Batt (13, 23)

Batt (23, 14) = Batt (14, 23)

$$\text{Batt } (23,\ 26) = \frac{S_{51}}{Z_{26}}$$

Batt (23, 15) = Batt (15, 23)

Batt (23, 16) = Batt (16, 23)

Batt (23, 17) = Batt (17, 23)

Batt (23, 18) = Batt (18, 23)

ST = 1.0

If $S_{58} = S_{62} = 0$

Then ST = 0

Batt (23, 22) = Batt (22, 23)

Batt (23, 4) = Batt (4, 23)

Batt (23, 2) = Batt (2, 23)

Batt (23, 20) = Batt (20, 23)

Batt (23, 1) = Batt (1, 23)

Batt (23, 3) = Batt (3, 23)

Batt (23, 23) = consist of subtracting all preceding batteries.

$$\text{Batt } (23,\ 32) = \frac{S_{63}\ (E_{PBA})}{R_{21} + R_{20}} + \text{Batt } (23,\ 7)\ E_{BC} + \frac{S_{36}\ (E_{BA})}{R_{17} + R_{18}} + \frac{S_{62}\ (E_{PBB})}{R_{32} + R_{33}} + \frac{S_{61}\ (E_{BB})}{R_{35} + R_{36}}$$

NODE 24:

$I_{74} - I_{71} - I_{65} = 0$

$$\frac{(E_{20} + E_{FC2} - E_{24})\ S_{74}}{R_{68} + R_{52}} - \frac{(E_{24} - E_{27})\ S_{80}}{R_{63} + R_{RCR4}} - \frac{(E_{24} - E_{28})\ S_{70}}{R_{59} + R_{RCR3}} = 0$$

Batt (24, 20) = Batt (20, 24)

$$\text{Batt } (24,\ 27) = \frac{S_{80}}{R_{63} + R_{RCR4}}$$

$$\text{Batt } (24,\ 28) = \frac{S_{70}}{R_{59} + R_{RCR3}}$$

Batt (24, 24) = - Batt (24, 20) - Batt (24, 27) - Batt (24, 28)

Batt (24, 32) = - Batt (24, 20) E_{FC2}

Node 25:

$I_{75} - I_{72} - I_{66} = 0$

$$\frac{(E_{20} - E_{25} + E_{FC3})\, S_{75}}{R_{66} + R_{67}} - \frac{(E_{25} - E_{27})\, S_{81}}{R_{64} + R_{RCR6}} - \frac{(E_{25} - E_{28})\, S_{71}}{R_{60} + R_{RCR5}} = 0$$

Batt (25, 20) = Batt (20, 25)

$$\text{Batt }(25,\ 27) = \frac{S_{81}}{R_{64} + R_{RCR6}}$$

$$\text{Batt }(25,\ 28) = \frac{S_{71}}{R_{60} + R_{RCR5}}$$

Batt (25, 25) = - Batt (25, 20) - Batt (25, 27) - Batt (25, 28)

Batt (25, 32) = - Batt (25, 20) E_{FC3}

Node 26:

$I_{52} - I_{53} = 0$

$$\frac{(E_7 - E_{26})\, S_{82}}{R_{25}} - \frac{(E_{26} - E_{23})\, S_{51}}{Z_{26}} = 0$$

Batt (26, 7) = Batt (7, 26)

Batt (26, 23) = Batt (23, 26)

Batt (26, 26) = - Batt (26, 7) - Batt (26, 23)

[redacted]

Node 27:

$$I_{70} + I_{71} + I_{72} - I_{69} - I_{67} - I_{60} = 0$$

$$\frac{(E_{31} - E_{27})\, S_{79}}{R_{62} + R_{RCR2}} + \frac{(E_{24} - E_{27})\, S_{80}}{R_{63} + R_{RCR4}} + \frac{(E_{25} - E_{27})\, S_{81}}{R_{64} + R_{RCR6}} - \frac{(E_{27} - E_{30})\, S_{78}}{R_{61}}$$

$$- \frac{(E_{27} - E_{20})\, S_{77}}{Z_{27}} - \frac{(E_{27} - E_{2})\, S_{66}}{R_{56}} = 0$$

$$\text{Batt } (27,\ 31) = \frac{S_{79}}{R_{62} + R_{RCR2}}$$

Batt (27, 24) = Batt (24, 27)

Batt (27, 25) = Batt (25, 27)

$$\text{Batt } (27,\ 30) = \frac{S_{78}}{R_{61}}$$

Batt (27, 20) = Batt (20, 27)

Batt (27, 2) = Batt (2, 27)

Batt (27, 27) = - Batt (27, 24) - Batt (27, 25) - Batt (27, 30)

- Batt (27, 20) - Batt (27, 2) - Batt (27, 31)

Node 28:

$$I_{64} + I_{65} + I_{66} - I_{63} - I_{67} - I_{61} = 0$$

$$\frac{(E_{31} - E_{28})\,S_{69}}{R_{58} + R_{RCR1}} + \frac{(E_{24} - E_{28})\,S_{70}}{R_{59} + R_{RCR3}} + \frac{(E_{25} - E_{28})\,S_{71}}{R_{60} + R_{RCR5}} - \frac{(E_{28} - E_{29})\,S_{68}}{R_{57}}$$

$$- \frac{(E_{28} - E_{20})\,S_{67}}{Z_{28}} - \frac{(E_{28} - E_{1})\,S_{65}}{R_{55}} = 0$$

$$\text{Batt}\,(28,\ 31) = \frac{S_{69}}{R_{58} + R_{RCR1}}$$

$$\text{Batt}\,(28,\ 29) = \frac{S_{68}}{R_{57}}$$

Batt (28, 20) = Batt (20, 28)

Batt (28, 1) = Batt (1, 28)

Batt (28, 28) = - Batt (28, 31) - Batt (28, 29) - Batt (28, 20) - Batt (28, 1)

Batt (28, 24) = Batt (24, 28)

Batt (28, 25) = Batt (25, 28)

Node 29:

$$I_{63} - I_{78} = 0$$

$$\frac{(E_{28} - E_{29})\, S_{68}}{R_{57}} - \frac{(E_{29} - E_{20})\, S_{72}}{R_{34} + Z_{29}} = 0$$

Batt (29, 28) = Batt (28, 29)

Batt (29, 20) = Batt (20, 29)

Batt (29, 29) = - Batt (29, 28) - Batt (29, 20)

Node 30:

$$I_{69} - I_{79} = 0$$

$$\frac{(E_{27} - E_{30})\ S_{78}}{R_{61}} - \frac{(E_{30} - E_{20})\ S_{76}}{R_{65} + Z_{30}} = 0$$

Batt (30, 27) = Batt (27, 30)

Batt (30, 20) = Batt (20, 30)

Batt (30, 30) = - Batt (30, 27) - Batt (30, 20)

Node 31:

$I_{73} - I_{64} - I_{70} = 0$

$$\frac{(E_{20} - E_{31} + E_{FC1})\, S_{73}}{R_{53} + R_{54}} - \frac{(E_{31} - E_{28})\, S_{69}}{R_{58} + R_{RCR1}} - \frac{(E_{31} - E_{27})\, S_{79}}{R_{62} + R_{RCR2}} = 0$$

Batt (31, 20) = Batt (20, 31)

Batt (31, 28) = Batt (28, 31)

Batt (31, 27) = Batt (27, 31)

Batt (31, 31) = - Batt (31, 20) - Batt (31, 28) - Batt (31, 27)

Batt (31, 32) = - Batt (31, 20) E_{FC1}